2004
ARO IN REVIEW

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U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

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This report is intended to be a single-source document describing the U.S. Army Research Office (ARO) research programs for FY04. It includes:

- A brief review of the strategy employed to guide ARO research investments and noteworthy issues affecting the implementation of that strategy;

- Statistical information on 6.1 funding and program proposal activity; and

- Research trends and accomplishments of the individual ARO scientific divisions.

The programs described are direct-funded from Army Program Elements "Defense Research Sciences", "University/Industrial Research Centers" and "University Research Initiatives" (URI). Research supported with customer funds (e.g., the Defense Advanced Research Projects Agency) is included in the description of closely aligned ARO programs as appropriate.

Although the Army Material Command's Research, Development and Engineering Command (RDECOM) is the primary user of the ARO research program, ARO also supports research on behalf of the Army Corps of Engineers, the Army Medical Research and Materiel Command, and other Army Commands and Department of Defense (DoD) agencies. Coordination and monitoring of the ARO extramural program by the Army Research Laboratory Directorates; Research, Development and Engineering Centers; and other Army laboratories ensure a highly productive and cost-effective Army research effort. University Affiliated Research Centers (UARC) and Multidisciplinary University Research Initiative (MURI) centers benefit from the expertise and guidance provided by the Army Research Laboratory Directorates, Research, Development and Engineering Centers, and other DoD, academic, and industry representatives who serve on Executive Steering Boards and Technical Assessment Councils for each university center. The Office of the Secretary of Defense (OSD) research programs managed by ARO fall under the executive oversight of the Defense Basic Research Panel. In FY04 this panel was chaired by the ARO Director. Other members on this panel include the Director of Research, Office of the Deputy Under Secretary of Defense (Science and Technology) and representatives from the Office of Naval Research (ONR), the Air Force Office of Scientific Research (AFOSR) and the Defense Advanced Research Projects Agency.

ARO INVESTMENT STRATEGY

The U.S. Army Research Office (ARO) strategic vision is to conduct an aggressive basic science research program on behalf of the Army so that cutting-edge scientific discoveries and the general store of scientific knowledge will be optimally used to develop and improve weapons systems that establish land force dominance. Programs are formulated in consultation with the Army Research Laboratory Directorates; the Research, Development and Engineering Command's Research, Development and Engineering Centers; the Army Medical Research and Materiel Command; the Army Corps of Engineers; and the Army Research Institute for the Behavioral and Social Sciences. The programs are also jointly coordinated and planned through the Defense Science and Technology Reliance process under the Basic Research Panel.

Strategies to meet the vision are:

- Accelerate research results transition to applications in all stages of the research and development cycle.

- Strengthen academic, industrial, and nonprofit laboratories research infrastructures, which serve the Army.

- Focus on those research topics that support technologies vital to the Army's future force, combating terrorism and new emerging threats.

- Direct efforts in research areas relating to new opportunities for Army applications and which underscore the role of affordability and dual-use, especially as they provide new Force Operating Capabilities and emerging threats.

- Leverage the science and technology of other defense and Government laboratories, academia and industry, and appropriate organizations of our allies.

- Foster scientists and engineers training in the disciplines critical to Army needs.

- Actively seek creative approaches to enhance education and research programs at Historically Black Colleges and Universities and at Minority Institutions.

To implement this strategy, the ARO extramural research program uses single investigator efforts, University Affiliated Research Centers, and specially tailored outreach programs. Each approach has its own objectives and set of advantages. This strategy is also employed by the ARO to the maximum extent possible in planning outreach programs sponsored by the Office of Deputy Undersecretary of Defense (Science and Technology).

GENERAL INFORMATION

This section of the report addresses issues affecting the implementation of the research programs managed by the U.S. Army Research Office (ARO) in FY04.

Project BH57 represents the core research budget provided to ARO by the Army. The actual release of funds to Project BH57 this year was $52.9M. This represented about a $.8M increase over the FY03 amount making the money available for single investigator research about the same as in the previous year.

Through funds provided by ARO Project BH59, ARO continued to fund the Institute for Collaborative Biotechnologies (ICB) at the University of California – Santa Barbara. This University Affiliate Research Center focuses sensors, electronics and information processing biotechnology and the underpinning biotechnology fundamentals. In FY04 the ICB received $7.6M in 6.1 funding and should have a sustained, multi-year budget of approximately $7M annually. The two additional universities selected as ICB partners in FY03; Massachusetts Institute of Technology and California Institute of Technology, also continued receiving funding in FY04.

For nearly all of the 1990's, the funding from the Office of the Secretary of Defense (OSD) University Research Initiative (URI) exceeded those provided to the ARO by the Army. However, in FY04, the OSD funding was devolved and now comes to ARO as Army funding. They still fund the same programs as in the past so the restrictions on some of the funds still exists. For example, new research topics under the Multidisciplinary University Research Initiative Program are restricted to certain DoD Strategic Research Areas or other approved OSD research topics.

Just as in the previous year, the largest single source of research funding to ARO in FY04 was the Defense Advanced Research Projects Agency (DARPA). DARPA provides funds for such key research areas as compact, lightweight power sources, smart structures, optoelectronics, nanostructure fabrication, multi-agent systems, and materials for photonic systems. The ARO Physics Division continued to manage a multi-million dollar program in quantum computing with funds from both DARPA and the National Security Agency.

SMALL BUSINESS INNOVATION RESEARCH (SBIR) AND SMALL BUSINESS TECHNOLOGY TRANSFER (STTR) PROGRAMS

Congress established the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs to provide small businesses and research institutions with opportunities to participate in government-sponsored research and development. SBIR was established in 1982 and has been reauthorized through 2008, while STTR was established in 1994 and is currently authorized through 2009.

The goals of the SBIR and STTR programs are: (1) stimulate technological innovation, (2) increase small business participation in federal R&D, (3) increase private sector

commercialization of technology developed through federal R&D, and (4) foster and encourage participation in federal R&D by businesses that are owned by women and socially and economically disadvantaged individuals. The STTR Program has the additional goal of encouraging small companies and researchers at academic institutions and non-profit research institutions to work together to transition emerging technical ideas from the laboratory to the marketplace.

Congressional mandate requires that all federal agencies with an annual extramural R&D budget exceeding $100 million participate in the SBIR program. The SBIR budget is computed as 2.5 percent of the agency's extramural R&D budget. The Army SBIR budget for FY05 is expected to be $233 million. The STTR budget is computed as .3 percent of the agency's extramural R&D budget. The Army STTR budget for FY05 is expected to be $28 million.

The U.S. Small Business Administration (SBA) is responsible for the government-wide SBIR and STTR Programs. The SBA is responsible for developing top-level policy for the programs and reporting SBIR/STTR data and statistics to the Administration and Congress. Each federal agency manages its SBIR/STTR Program separately. The Army participates under the Department of Defense (DoD) SBIR/STTR Program structure.

The SBIR Program is open to any small business, defined as a business having no more than 500 employees (including all affiliates), which is operated in the USA and at least 51% owned by a U.S. citizen or permanent resident alien. The small business may subcontract a portion of its work, so long as the small business "prime" performs at least two-thirds of the Phase I work and half of the Phase II work. For the purposes of determining compliance, percent of work is usually measured by both direct and indirect costs; however, the actual method of measurement will be verified during contract negotiations.

The Principal Investigator (PI) for each SBIR and STTR Phase I and Phase II effort must be primarily employed by the small business, meaning that more than half of his/her time is spent with the small business. Primary employment with a small business precludes full-time employment at any other organization. Any deviations from these requirements must be approved during contract negotiations.

The STTR Program is open to any team consisting of a small business (as defined above) and a research institute. The research institute may be any U.S.-based nonprofit research institution, federally funded research and development center (FFRDC), or university or college. The small business must perform at least 40% of the Phase I and Phase II work. The research institute must perform at least 30% of the Phase I and Phase II work. Up to 30% of the work may be subcontracted.

For both programs, the Phase I and Phase II work must be performed in the United States, to include the Commonwealth of Puerto Rico, the Commonwealth of the Northern Mariana Islands, the Trust Territory of the Pacific Islands, and the District of Columbia.

Each year, along with other DoD components, the Army generates and publishes a set of high-priority topics in an SBIR solicitation and invites small businesses to submit proposals dealing with these topics. The topics reflect the user community's interests and Force Operating Capabilities (FOCs) as expressed in TRADOC PAMPHLET 525-66. All Army SBIR topics will also reflect Future Combat Systems (FCS)/Future Force (FF) S&T needs, and at the same time be aligned with Science and Technology Objectives **(STOs),** Advanced Technology Demonstrations **(ATDs),** and Advanced Concept Technology Demonstrations **(ACTDs).** A LOGTECH Panel has an opportunity to endorse SBIR topics. 50% of Army's topics must be endorsed or co-authored by an Acquisition Program (PM or PEO).

Both programs use a three-phase process, reflecting the high degree of technical risk involved in developing and commercializing cutting edge technologies.

Phase I is a feasibility study that determines the scientific, technical, and commercial merit and feasibility of a selected concept. Phase I projects are competitively selected from proposals submitted against annual solicitations. Each solicitation contains topics seeking specific solutions to stated government needs. The Army publishes its SBIR topics in the second of three DoD SBIR solicitations each year, which generally opens in the summer.

The Army likewise publishes its STTR topics in an annual DoD STTR solicitation, which generally opens in January of each year. The Army SBIR/STTR Phase I processes are highly competitive, with about one out of ten proposals receiving awards.

Phase II represents a major research and development effort, culminating in a well-defined deliverable prototype (i.e., a technology, product, or service). The Phase II selection process is also highly competitive. Successful Phase I contractors are invited to submit Phase II proposals as there are no separate Phase II solicitations. Approximately 50% of Phase II proposals are selected for award.

In **Phase II Plus,** the Army provides up to $250,000 in matching SBIR funds for an existing Phase II effort to be extended for up to one year to perform additional research and development.

In **Phase III**, the small business or research institute is expected to obtain funding from the private sector and/or non-SBIR government sources to develop the prototype into a viable product or service for sale in the military or private sector markets.

There are several basic differences between the SBIR and STTR Programs within the above 3-phase structure. The following table compares the two programs.

PHASES	SBIR	STTR
Phase I	• 6 months, $70,000 max • 4-month option (at Government's discretion if Phase II proposal is selected), $50k max, to fund interim Phase II efforts.	• Six months, $100,000 max • No options
Phase II	• 2 years, $730,000 max	• 2 years, $750,000 max beginning in FY04
Phase II PLUS	• 1 year, $250,000 max (subject to third-party matching funds)	
Phase III	• No time limit • No SBIR funds	• No time limit • No STTR funds

Figure VI–1. Phases of SBIR/STTR Programs

For more information about Army–specific SBIR/STTR, visit http://www.aro.army.mil/arowash/rt. and the DoD SBIR/STTR Program Office maintains a Web site with more information about the SBIR/STTR programs at http://www.acq.osd.mil/sadbu/sbir.

The Army is the Executive Agent for coordination of the chemical and biological defense (CBD) program. The Army executes the CBD SBIR program with oversight provided by the Defense Threat Reduction Agency. The CBD SBIR topics touch on both medical and non-medical aspects of CBD. As lead agency, the Army coordinates tri-service/U.S. Special Operations Command (SOCOM) efforts related to developing solicitation topics and the receipt, evaluation, selection, and award of SBIR Phase I and II proposals.

Chemical and Biological Defense (CBD) Program - In response to Congressional interest in the readiness and effectiveness of U.S. Nuclear, Biological and Chemical (NBC) warfare defenses, Public Law 103-160 directed that the DoD consolidate management and oversight of the CBD Program into a single office within OSD. In FY04, the CBD SBIR Program underwent reorganization to incorporate S&T oversight provided by the Defense Threat Reduction Agency (DTRA) Joint Science and Technology Office (JSTO). Program Management for the SBIR portion of the program is provided by the Army Research Office-Washington (ARO-W). The CBD SBIR Program received $11.2 million from DTRA JSTO for FY04. These funds were allocated to four DoD agencies (Army, Navy, Air Force, and DTRA) that participated in the CBD SBIR Program in FY04. A special section of CBD SBIR topics, from across DoD, is published each year in the first of the three annual DoD SBIR Solicitations. A total of 27 Phase I proposals were selected for a CBD SBIR award out of 271 proposals submitted, totaling an investment of $1,885,739 (ARO- $279,965). For Phase II proposals, a total of 12 were selected for contract award out 16 proposals submitted, totaling an investment of $5,028,553 for new projects and $3,317,893 for ongoing projects, of which ARO received $910,137.

Future Combat Systems (FCS)/Future Force (FF) **–** In support of the CSA's FCS/FF initiatives, all Army SBIR topics are aligned with an FCS/FF technology area and support the science and technology objectives, advanced technology demonstrations, and advanced concepts and technology demonstrations. We began this process with the topics so that the Phase I and Phase II projects will flow from them.

Training and Doctrine Command Battle Labs - The Army Training and Doctrine Command (TRADOC) established the Battle Labs to demonstrate and assess new doctrines, strategies, warfighting methods, and technologies within the context of the future Army. The Battle Labs conduct live, virtual, and constructive simulations to determine the warfighting merits of new ideas, concepts, and technologies – including those of industry. The Battle Labs are organized around the major battlefield dynamics: Air Maneuver, Air and Missile Defense, Battle Command, Combat Service Support, Depth and Simultaneous Attack, Dismounted Battlespace, Maneuver Support, Mounted Maneuver Battlespace, and Space and Missile Defense.

Short Term Innovative Research Program - The objectives of the Short Term Innovative Research (STIR) Program are to find innovative ideas in basic research. Proposed research may be for the continuation or the natural outgrowth of experimental or theoretical exploration. Research proposals are sought from educational institutions, nonprofit organizations, or private industry.

University Research Initiative (URI) and other OSD Programs - OSD 6.1 direct funding to ARO through the Office of the Director for Defense Research & Engineering (ODDRE) generally exceeds the level of Army 6.1 direct funds awarded to universities by ARO. However, more than the magnitude of dollars, the scope and variability of this activity in terms of objectives (research, instrumentation, education, etc) and targeted groups (minority institutions, selected states, etc) add a complexity to planning and execution far in excess of ARO's Army-funded programs.

Current OSD-budgeted initiatives include:

- Multidisciplinary University Research Initiative (MURI) Program;

- Defense Experimental Program to Stimulate Competitive Research (DEPSCoR);

- Defense University Research Instrumentation Program (DURIP);

- National Defense Science and Engineering Graduate (NDSEG) Fellowships;

- Infrastructure Support Program (ISP) for Historically Black Colleges & Universities and Minority Institutions (HBCU/MI); and

- Presidential Early Career Awards for Scientists and Engineers (PECASE).

Each of these ODDRE-mandated activities has a different focus and/or different target audience. The ARO has been designated by the Director of Research/ODDRE as the lead agency for the implementation of two of the DoD programs on behalf of the three Services plus the Agencies of the Department of Defense. These are the DEPSCoR and ISP-for-HBCU/MI activities. A brief description of each of the multi-year programs follows.

Defense Experimental Program to Stimulate Competitive Research (DEPSCoR) - The DEPSCoR program improves the capabilities of universities in selected states by supporting research and the education of scientist and engineers in areas important to national defense in general and the Army. DEPSCoR is specifically designed to expand research opportunities in states that have traditionally received the least funding in federal support for university research. Academic researchers in Alaska, Arkansas, Delaware, Hawaii, Idaho, Kansas, Kentucky, Maine, Montana, Nebraska, Nevada, North Dakota, Oklahoma, the Commonwealth of Puerto Rico, South Carolina, South Dakota, the US Virgin Islands, Tennessee, Vermont, West Virginia, and Wyoming are eligible to receive awards under this competition. The work performed within this program directly supports Future Force requirements by providing the enabling technologies which will make development of Future Force equipment possible. The program provides the nation with a broad base, basic research infrastructure built on the single investigators within the current academic infrastructure. It thereby bypasses the high administrative burden often associated with large, resource intensive single focus efforts. Additionally, the program reflects remarkable flexibility and possesses a track record of innovation since the program is open to all topics described in the traditional Broad Agency Announcements and is open to any researcher within the designated states. NSF state committees screen the proposals in the context of state research infrastructure needs and forward them to the services for final selection and funding. The work is consistent with the Army Science and Technology Master Plan, the Army Modernization Plan, and Project Reliance. Twenty projects were competitively selected under the FY04 Defense Experimental Program to Stimulate Competitive Research (DEPSCoR) in 12 States $8.4 million to perform research in science and engineering fields

Historically Black College and Universities/Minority Institutions (HBCU/MI) - Programs for HBCU/MIs are a significant part of the ARO program. In 2004 ARO awarded over $23 million to minority institutions. This includes grants supported under the ARO core research program and several DoD programs that ARO implements on behalf of the Director of Defense Research and Engineering (DDR&E). These are discussed below:

- **ARO (Core-funded) HBCU/MI Program**: The ARO began its HBCU/MI program in 1980 with a $0.5 million set aside intended to encourage participation of HBCUs and MIs in its research programs. Each year since then ARO has reserved a portion of its research program for minority institutions. For the past several years the set aside has been over $1 million. This has been used to co-fund research projects of interest to, and selected by, the ARO scientific divisions under the Core broad agency announcement.

- **DoD-funded HBCU/MI Programs**: The DoD Infrastructure Support Program for HBCU/MI program was initiated under the Defense Authorization Act of 1991 (P.L.101-510, Section 832). Legislation prescribed a variety of research and educational initiatives intended to build infrastructure in science, mathematics, and engineering programs at HBCUs and MIs and enable them to participate more fully in defense research, as well as to recruit more students in scientific disciplines important to defense. Eligibility for the program is limited to institutions appearing on the US Department of Education list of Accredited Postsecondary Minority Institutions. Funding for the DoD Infrastructure Support Program ranges from $10 million to $15 million annually with approximately one half that amount available for new awards. All grants are awarded competitively. Examples of funding opportunities include:

    1. Instrumentation for research and/or education programs;
    2. Research and/or education centers and consortia;
    3. Collaborative research programs;
    4. Technical assistance programs; and
    5. Undergraduate scholarships, graduate fellowships, and faculty research fellowships.

The FY 04 Infrastructure Support Program supported thirteen new research grants and twelve instrumentation grants totaling over $6 million, and ongoing commitments to four research and education centers totaled over $3 million.

In addition to the Infrastructure Support Program discussed above, ARO implemented two additional FY04 programs for the DDR&E. These were Congressional set-asides for Hispanic-Serving Institutions (HSIs) and Tribal Colleges and Universities (TCUs). The program for HSIs awarded fifteen research and instrumentation grants totaling $3.969 million, and the program for TCUs awarded eight instrumentation grants totaling $2.3 million.

In summary, ARO awarded over $23 million to HBCUs and MIs in FY04. This includes the ARO-funded programs, the DoD-funded programs, as well as Congressionally-directed programs.

Multidisciplinary University Research Initiative (MURI) Program - The essential features of the MURI program are the same as those of the original URI but the scope of each award is generally larger and there are subsequently fewer awards with these annual solicitations. A typical MURI center is supported for five years at one million dollars per year. Also, unlike the previous URI program, selection of the Service research topics and the eventual awards are now closely reviewed and approved by ODDRE under a formal acquisition process. The Services compete for topics and awards based on the limited funds available. MURI funds are not allocated to the Services on any prescribed basis. Over the years the Army has fared quite well in these competitions, garnering more

topics and funding than the other Services. Topics that resulted in 9 newly funded Army centers for FY04 were:

- Hybrid Synthetic Biopolymers for Multifunctional Materials
- Hybrid Bio-Mechanical Systems
- Space-Time Processing for Enhanced Mobile Ad-Hoc Wireless Networking
- Design and Processing of Electret Structures
- Giga-Hertz Electromagnetic Wave Science and Devices for Advanced Battlefield Communications
- Micro Hovering Aerial Vehicles with an Invertebrate Vision Inspired Navigation System
- Nano-Engineered Energetic Materials
- Human Signatures for Personnel Detection
- Laboratory Instrumentation Design Research

Topics that the Army has entered in the somewhat abbreviated FY05 program announcement are:

- Cross-Disciplinary Approach to the Modeling, Analysis, and Control of Wireless Communications Networks
- Control of Networked Autonomous and Semi-Autonomous Vehicle Swarms Inspired by Nature
- Standoff Inverse Analysis and Manipulation of Electronic Systems (SIAMES)
- Training for the Networked Battlefield
- Quantum Imaging
- Advanced Magnetic Resonance Force Microscopy to Single Nuclear Spin Detection
- Material Engineering of Lattice-Mismatched Semiconductor Systems
- Enabling Science for Future Force Insensitive Munitions

Defense University Research Instrumentation Program (DURIP) - DURIP supports the purchase of state-of-the-art equipment that augments current university capabilities or develops new university capabilities to perform cutting-edge defense research. DURIP meets a critical need by enabling university researchers to purchase scientific equipment costing $50,000 or more to conduct DoD-relevant research. The researchers generally have difficulty purchasing instruments costing that much under their research contracts and grants. The work is consistent with the Army Science and Technology Master Plan (ASTMP), the Army Modernization Plan, and Project Reliance. In FY04, Department of Defense (DoD) wide, made 213 awards to 92 academic institutions are for a total of $43.5 million to academic institutions. Of that, the Army share was 63 awards at $10.8 million with the average award being $175,000.

National Defense Science and Engineering Graduate (NDSEG) Fellowship Program- The ARO participates along with the ONR and the AFOSR in the NDSEG Fellowship Program, which is administrated under a contract managed by the AFOSR. With approximately $5 million available to the Army in FY04, the ARO selected 53 NDSEG

Fellows who began their fellowships in the Fall of 2004. NDSEG Fellows may attend the university of their choice and are provided full tuition and fees and a stipend for three years. The average cost per fellowship is $128,000.

Presidential Early Career Award for Scientists and Engineers - The Army annually nominates two young investigators for the PECASE awards, which average $100,000 per year for five years.

YOUTH SCIENCE ACTIVITIES

Youth Science Activities - Whether it is providing a work/study experience, sponsoring tutorial classes during the summer, showcasing talented young high school scientists at symposia or judging student science fair projects, each of the Youth Science Programs sponsored by the Department of Army has one purpose in common – to increase the number of future adults capable of conducting research and development.

The Army's programs for the youth of this nation collectively reach more than 100,000 high school students throughout the United States, Puerto Rico and the DoD Schools of Europe and the Pacific. Students participating in the programs during this past fiscal year were awarded more than $380K in college tuition scholarships; savings bonds totaling in excess of $50K; expense paid trips to attend the London International Youth Science Forum, held at the University of London, the Operation Cherry Blossom Program in Kyoto and Tokyo, Japan and the International Mathematical Olympiad in Athens, Greece.

Additionally, 95 students served as interns and worked in university laboratories during the summer with selected mentors. More than 500 students participated in programs that offered enrichment classes in science, engineering and mathematics. Brief descriptions of these exciting and innovative programs follow:

The **Junior Science and Humanities Symposium (JSHS) Program** goals are to:

- promote research and experimentation in the sciences, mathematics, and engineering at the high school level;
- search out talented youth and their teachers, recognize their accomplishments at symposia, and encourage their continued interest and participation in the sciences, mathematics, and engineering; and
- publicly recognize the accomplishments of these talented youths.

The **Research and Engineering Apprenticeship Program (REAP)** is designed to offer historically under represented high school students the opportunity to expand their background and understanding of scientific research. This is accomplished by offering the student an internship, during the summer months, to participate in a work/study atmosphere with a mentor in a laboratory setting. The experience serves to motivate the student towards a career in science, mathematics or technology by providing a challenging science experience that is not readily available in high school.

The **Uninitiates' Introduction to Engineering (UNITE) Program** is an aggressive and effective program that encourages and assists under represented students in preparing for entrance into engineering schools. High school students are provided the opportunity, during the summer months, to participate in college-structured summer courses which provide hands on applications, participation in lectures, problem solving as well as tours of laboratories and private and governmental engineering facilities. The students are introduced to ways in which math and science are applied to real-world situations and how they are related to careers in engineering and technology. During this fiscal year the UNITE was held on five university campuses.

The **International Science and Engineering Fair (ISEF) Program** provides high school students the opportunity to present their projects, in competition with their peers, to Army judges who are special awards sponsors at these annual events. Each year, ROTC Units, Recruiting Battalions, Army Reservists and Army command/laboratory personnel serve as judges of student projects at more than 350 science fair competitions held throughout the United States and Puerto Rico. By participating in science fairs, the Army is able to encourage and stimulate talented students to consider careers in science and technology while simultaneously exposing these students to Army research and development opportunities.

Finally, the Department of Army provides the necessary funding for the travel of the team representing the United States at the **International Mathematical Olympiad.** Each year, thousands of high school students test their mathematical capabilities, and through progressive competition, six top-scoring students emerge to form the U.S. Olympiad team. The six-member team represents the United States in international competition with teams from more than eighty countries.

Picture 1: (back row) LTC David Camps and LTC Larnce Robinson. (front row left) Top Army Award winners, Anarghya Vardhana and Divya Nettimi, at the International Science and Engineering Fair. They will represent the U.S. at the annual Operation Cherry Blossom (OCB) program. Also shown in front row are Army awards presenter, MG Douglas Dollar and Lauren Smith, Alternate OCB winner. [The expense paid trip to Tokyo and Kyoto, Japan, will include scientific and cultural tours and attendance at the Japan Student Science Awards ceremony. Each student received $3,000 in savings bonds, a certificate of achievement signed by the Secretary of Army, and a gold medallion for science, engineering, mathematics excellence.]

ARO SUPPORT TO ARMY TRANSFORMATION

THE IMPERATIVE TO TRANSFORM

The Army is transforming now. Today, the Army must transform to a campaign-quality force with joint and expeditionary capabilities to provide relevant and ready land power to combatant commanders and the Joint Force. At the same time, it must also sustain operational support to forces fighting the global war on terrorism while maintaining the quality of the all-volunteer force.

The Army is focusing its efforts to enhance the capabilities of frontline Soldiers and units to meet the requirements of the full range of Army strategic commitments. The 2004

PROGRAM IMPLEMENTATION

Army Transformation Roadmap describes the path the Army is taking to adapt its institutions and capabilities. It also depicts how the Army will transform in a time of war — balancing current and future needs.

ARMY TRANSFORMATION STRATEGY AND ARMY CAMPAIGN PLAN

Transformation is a process that shapes the changing nature of military competition and cooperation through new combinations of concepts, capabilities, people and organizations. It employs the nation's advantages and protects against asymmetric vulnerabilities. It sustains the U.S. strategic position, thus helping peace and stability in the world. The Army's transformation strategy has three components: (1) transformed culture, (2) transformed processes, and (3) transformed capabilities.

The Army also is developing the right mix of force application capabilities required for modern conflict. At the same time, the Army is reorganizing its CS/CSS capabilities into modular packages. This will allow combatant commanders to more rapidly draw upon discrete Army capability modules. This process will create capabilities that provide the Joint Force with strategically agile and flexible arrangements of combat power.

The following are representative ARO-supported research programs that support both the Interim Force and the Future Force.

INTERIM FORCE	FUTURE FORCE
▪ Compact power generation through thermophotovoltaics and fuel cells	▪ Microturbines for compact power
▪ Improved engine performance through active control of dynamical processes	▪ Terrahertz electronics for advanced communications
▪ Enhanced combat information processor to solve information overload	▪ Multi-functional armor for future combat systems
▪ Smart rotor blades for enhanced rotorcraft maneuverability	▪ Optical limiting windows for sensor protection
▪ Photonic band engineering for enhanced antenna performance	▪ Alternative KE penetrator materials
▪ Designer propellants at reduced cost and increased safety	▪ Chemical/biological vehicle shield
	▪ Genetically engineered material for biomolecular optoelectronics
	▪ All solid state FCS radar/illuminator (K-band)
	▪ High performance ETC propulsions

ARMY RESEARCH OFFICE CORE PROGRAMS

ARO programs supported with Army 6.1 funds generally fall within two broad categories: single investigator programs (supported with Project BH57 funds) and Army Centers of Excellence (COE) (supported with Project BH59 funds). Collectively, these two programs are referred to as the ARO core program. The following tables show the proposal activity of the ARO core program. Roughly one-third of the single investigator grants turn over annually. In contrast, the commitment of an Army COE is longer term with more stable funding.

ARO CORE PROGRAM PROPOSAL ACTIONS				
	RECEIVED	**ACCEPTED**	**DECLINED**	**WITHDRAWN**
Chemistry	60	23	8	2
Computing & Information Sciences	59	21	8	1
Electronics	36	21	3	0
Environmental Sciences	36	12	4	1
Life Science	45	16	6	1
Materials Science	57	23	12	2
Mathematical Sciences	47	21	6	1
Mechanical Sciences	64	12	11	1
Physics	53	25	7	0
Research Technology Integration	3	2	0	0
TOTAL	**460**	**176**	**65**	**9**

Note: The total of proposals accepted, rejected, or withdrawn does not equal the total received because proposals are not necessarily acted upon during the year of receipt. ARO proposal actions are the period 1 October 2003 through 30 September 2004. "Core Program" is defined as single investigator research (excluding special programs) supported with Army Project BH57 funds.

ARO FY04 FUNDING

CORE PROGRAMS	ALLOTMENT
Chemistry	$ 4,359,746
Computer and Information Sciences	$ 4,027,023
Electronics	$ 4,475,365
Environmental Science	$ 2,067,705
Life Sciences	$ 3,502,000
Materials Science	$ 4,636,498
Mathematical Sciences	$ 4,143,972
Mechanical Sciences	$ 4,107,342
Physics	$ 4,483,999
SUBTOTAL CORE PROGRAMS	**$ 35,803,650**

SPECIAL PROGRAMS	ALLOTMENT
Senior Research Scientist Research Programs	$ 439,692
National Research Council Associates Program	$ 632,000
Historically Black College & University/Minority Institution	$ 1,200,000
European Research Office	$ 50,000
Far East Office	$ 50,000
In-House Operations	$ 14,705,992
Subtotal Special Programs	**$ 17,077,684**
TOTAL PROJECT BH57 FUNDS	**$ 52,881,334**

OFFICE OF THE SECRETARY OF DEFENSE DIRECT-FUNDED PROGRAMS	ALLOTMENT
Defense Experimental Program to Stimulate Competitive Research	$ 2,889,000
OSD Small Business Innovation Research/Small Business Technology Transfer	$ 1,390,102
OSD Historically Black Colleges &University/ Minority Institutions	$ 16,899,000
TOTAL OSD DIRECT FUNDS	**$ 21,178,102**

ARMY AND OTHER DIRECT FUNDED PROGRAMS	ALLOTMENT
Critical Infrastructure Protection	$ 6,247,254
Multidisciplinary University Research Initiative Program	$ 40,365,153
National Nanotechnology Initiative	$ 3,727,298
Presidential Early Career Awards for Scientists Engineers	$ 909,097
Defense University Research Instrumentation Program	$ 10,940,428
University Research Initiative Support	$ 68,770
Institute for Collaborative Biotechnologies (ICB)	$ 7,595,540
eCybermission	$ 4,988,840
HBCU/MI – Battlelab Centers	$ 2,384,920
Institute for Creative Technology (ICT)	$ 11,655,000
Institute for Soldier Nanotechnology (ISN)	$ 9,446,000
Board of Army Science and Technology (BAST)	$ 1,249,000
Small Business Technology Transfer (STTR)	$ 16,611,828
Small Business Innovation Research (SBIR)	$ 14,600,466
Intellectual Property/SBIR Support	$ 1,120,056
Youth Science Activities	$ 1,604,000
Field Assistance in Science and Technology	$ 26,020
Lapsed Year Funding	$ 16,666
Defense Advanced Research Projects Agency (DARPA)	$ 81,155,279
Other Customer	$ 61,225,889
TOTAL ARMY AND OTHER RDT&E FUNDS	**$ 275,937,504**

FY04 CONGRESSIONAL ADDS	ALLOTMENT
Perpetually Assured Information Security (PASIS)	$ 5,874,940
Advanced Deployable Nano-Sensors	$ 1,156,010
Biofilms – Terrorist Agents in Water	$ 2,022,240
Buffalo Bioinformatics	$ 1,156,000
Desert Terrain Analysis	$ 2,888,580
Nano-Materials Research	$ 962,230
Anti-Corrosion Studies	$ 962,800
National Security Training	$ 962,800
Bioinformatics Research	$ 1,157,000
Defense Commercialization Research Initiative	$ 4,812,000
Desert Environment Research	$ 1,634,960
Institute of Bioengineering and Nanoscience in Advanced Medicine	$ 2,409,000
Institute for Entrepreneurial Excellence Technology	$ 1,474,000
MEMS Sensor for Rolling Elements	$ 1,347,440
Army Centers of Excellence	$ 1,444,700
Congressional Add for Institute of Creative Technology (ICT)	$ 1,348,000
TOTAL FY04 CONGRESSIONAL ADDS	**$ 31,612,700**
TOTAL ARO FY04 PROGRAM	**$ 381,609,640**

GENERAL INFORMATION

The Scientific Services Program (SSP) is implemented by a contract with Battelle. The program provides a rapid means for DoD and OGA researchers and managers to acquire short-term services from scientists and analysts. Through the SSP, these individuals provide the government task sponsors with results and solutions from well-defined studies, analyses, evaluations, interpretations, and assessments. Task performers include independents (non-affiliated self-employed persons), academics, small and large businesses from industry. The program provided services in FY04 in the following SSP subprogram elements:

- Scientific and Technical Analysis Services (STAS);

- Faculty Research and Engineering Program (FREP);

- High School Science and Mathematics Faculty Program (HSSMFP); and

- Conferences, Workshops, and Symposia (CW&S).

The largest category, STAS, provides nonpersonal, intermittent, short-term scientific and technical support services. Tasks under this category provide the solution to problems related to research and development of various activities within the Government, in particular, the Department of Defense. The primary intent of the FREP and HSSMFP is to introduce university, college, and high school faculty to Army laboratories, centers, and agencies to have them participate in research being performed within those organizations during the summer months. The SSP also provides services for organizing and administering conferences, workshops, and symposia of interest to any Federal agency. The commands/agencies served under the program and the number of new tasks awarded, during the period 1 October 2003 through 30 September 2004 are provided in the table at the end of this section.

Examples of Tasks Awarded through the Scientific Services Program:

The Scientific Services Program (SSP) awards tasks in a wide variety of technical areas ranging from mathematical and computer sciences, education and training, to studies in life sciences and chemistry related to Weapons of Mass Destruction (WMD). Approximately 28% of the tasks awarded in FY04 were related to WMD casualty care/management, agent detection/analysis, and force protection. The Army Research Office (ARO) conducted an Army/DARPA workshop on metrics and standards for evaluation and comparison of chemical warfare agent (CWA) detectors (CW&S Task Control Number (TCN) 04132). The Army Medical Research and Materiel Command (MRMC), Army Medical Research Institute for Chemical Defense (AMRICD) explored the biophysical and biochemical properties of different prophylactic drugs reacting with different CWAs (STAS TCN 04126). MRMC Walter Reed Army Institute of Research (WRAIR) conducted an investigation of medical treatments for casualties from WMD biological and chemical agents (STAS TCN 04-059). WRAIR also developed methods and sample analytical methodologies to support evaluation of oximes and drugs to protect against CWAs in vitro and in vivo (TCN 04113). The U.S. Army Research & Development Command (RDECOM), Natick Soldier Center (NSC) investigated new polyoxometalates for use in chemical detoxifying coatings (STAS TCN 04063).

Force protection, personnel, training, and performance in combat evaluation related tasks accounted for 25% of the total FY04 task count. The U.S. Navy Medical Center in San Diego CA (NMCSD) conducted an investigation of the nutritional supplement N-acetylcsteine (NAC) as an adjunct to hearing protection devices (HPDs) for preventing noise induced hearing loss (NIHL) in soldiers exposed to military noise (STAS TCNs 04005, 04010-04012, 04015, 04016, 04023, and 04036). MRMC AARL performed a human factors analysis of the Special Medical Emergency Evaluation Device (SMEED) for usage aboard the Army Medical Evacuation (MEDEVAC) Helicopters (STAS TCN 04112). U.S. Navy Personnel Center (NPC) studied the role of social support in first term sailors' attrition from recruit training including conceptualization of the problem and development of a pilot intervention methodology (STAS 04167).

Approximately 21% of the FY04 SSP tasks supported the warfighter in combat, current and future weapon systems through materials development, manufacturing, soldier - equipment interface performance measurement and human factors evaluation. MRMC U.S. Army Institute of Surgical Research (USAISR) studied molecular pharmacology and pharmacokinetics of drugs and supplements to ameliorate hemorrhagic shock (STAS TCN 04022). Army Research Laboratory (ARL) Weapons and Materials Research Directorate (WMRD) performed a human factors and combat effectiveness evaluations of the XM8 and XM25 weapon systems (STAS TCN 04026). MRMC Army Aviation Research Laboratory (AARL) investigated design issues associated with glass cockpit crew stations (FREP TCN 04041). AARL also reviewed performance of the HGU-56/P helmet (STAS 04064) and conducted intelligibility testing of high frequency speech and hearing in Army aviators (FREP 04073). The U.S. Army Tank-automotive and Armaments Command (TACOM), Tank and Automotive Research, Development and Engineering Center (TARDEC) conducted a study of the complexity and reliability issues in the development of dataflow architecture for human supervisory control of semi-autonomous ground vehicles (STAS 04055). RDECOM NSC investigated hydrogen conversion mechanisms for the Remote Unit Self Heating Meal (RUSHM) (HSSMFP TCN 04082)

Environmental related work accounted for approximately 14% of FY04 SSP tasks. Headquarters Department of Army, Army Environmental Policy Institute identified and analyzed world wide emerging environmental issues affecting the U.S. military resulting from international treaties (STAS TCN 04075). U.S. Army Corpse of Engineers (HQUSACE), Engineering Research & Development Center (ERDC) investigated stabilization of heavy metals in soils, concrete, and asphalt using topically applied treatments (FREP TCN 04077). USACE, Waterways Experimental Station (WES) conducted a study of manganese oxide coating in soil materials for heavy metals sequestration (FREP 04110). The Jacksonville FL USACE conducted an ecosystem monitoring and assessment for the Comprehensive Everglades Restoration Plan (CERP)/Restoration, Coordination and Verification (RECOVER) Program under STAS 04021. ARO performed analyses to determine the geochronology of igneous rocks from the Charges River Basin in Panama (STAS 04153).

Materials science and technology investigations and studies accounted for about 12% of the SSP tasks in FY04. ARL WMRD investigated adaptive control approaches to mitigate shock impact using piezoceramics (STAS TCN 04102). ARO conducted a literature review on the role of grain boundary surfaces in storing internal energy in nanocrystaline materials (STAS TCN 04138). ARO also conducted a comprehensive blast mitigation survey of all DoD, DOE and international existing and emerging materials technology (STAS TCN 04117).

SCIENTIFIC SERVICES PROGRAM

SPONSORS AND NUMBER OF TASKS BY SUBPROGRAM (FY04)

ACTIVITY*	STAS	FREP	HSSMF	CW&S	TOTAL
RDECOM					
AMRDEC	1	0	0	0	**1**
ARDEC	12	0	0	0	**12**
ARL	8	10	0	0	**18**
ARO	13	0	0	12	**25**
ECBC	1	1	1	0	**3**
NSC	4	1	2	0	**7**
FAST	0	1	0	0	**1**
TARDEC	7	2	3	0	**12**
TOTAL	**46**	**15**	**6**	**12**	**79**
MRMC					
AARL	6	3	1	0	**10**
AISR	1	0	0	0	**1**
ICD	10	1	0	0	**11**
IID		0	2	0	**2**
WRAIR	24	0	0	0	**23**
TOTAL	**41**	**4**	**3**	**0**	**48**
OSD/JPED-CBD	2	0	0	0	**2**
DOD-CBRN (PFPA)	1	0	0	0	**1**
DOD-EUCOM	1	0	0	0	**1**
HQ DA-AEPI	4	0	0	0	**4**
HQ USACE	5	0	0	0	**5**
ERDC	2	5	2	0	**9**
ATEC	1	0	0	0	**1**
USN	19	0	0	0	**19**
USMC	0	0	1	0	**1**
OGA	2	0	0	0	**2**
TOTALS	**124**	**24**	**12**	**12**	**172**

*ACRONYMS AND ABBREVIATIONS:

RDECOM-Research, Development & Engineering
    Command
AMRDEC-Aviation & Missile Research,
    Development & Engineering Center
ARDEC-Armaments Research, Development &
    Engineering Center
ARL-Army Research Laboratory
ARO-Army Research Office
ECBC-Edgewood Chemical Biological Center
NSC-Natick Soldier Center
FAST-Army Material Command Field Assistance in
    Science & Technology
TARDEC-Tank-Automotive Research, Development
    & Engineering Center
MRMC-Medical Research & Materiel Command
AARL-Aeromedical Research Laboratory

AISR-Institute of Surgical Research
ICD-Medical Research Institute of Chemical Defense
IID-Medical Research Institute of Infectious Diseases
WRAIR-Walter Reed Army Institute of Research
OSD-Office of Secretary of Defense
JPED-CBD- Joint Program Executive Office,
    Chemical & Biological Defense
CBRN - Chemical, Biological, Radiological,
    Nuclear Directorate
PFPA-Pentagon Force Protection Agency
EUCOM-European Command
AEPI-Army Environmental Policy Institute
USACE-Army Corp of Engineers
ERDC-Engineer Research & Development Center
ATEC-Topographic Engineering Center
USN-U.S. Navy

USMC-U.S. Marine Corps
OGA-Other Government Agencies

CHEMISTRY

Explosive Chemical Signatures in Soils - (Professor Miguel E. Castro-Rosario, University of Puerto Rico-Mayguez) – will be using his analytical laboratory facilities to characterize the fluorescence and photochemistry of TNT and related compounds on soil. This work will help develop the appropriate technologies for sensing explosives from landmines and IEDs.

Biocidal Coatings - (Professor Alan Russell, University of Pittsburg) – based on his development of biocidal compounds and experience in coatings, Professor Russell will prepare a biocidal coating or paint. This work will contribute to protection of the soldier from harmful organisms and bacteria.

Intermolecular Potentials - (Professor Krzysztof Szalewicz, University of Delaware) – using their newly developed Symmetry Adapted Perturbation Theory, this group will enable significantly improved Density Functionals for the computation of intermolecular potentials. Those potentials will be used for the computation of properties of energetic molecules in condensed phases.

Inhibiting Damage to Metal Surfaces - (Professor Emily Carter, Princeton University) – based on her development of an initio computational chemistry codes for molecules on surfaces, Professor Carter will determine the effect of small molecules on steel surfaces. This work will focus on likely species in firing gun barrels and explore the inhibition of barrel erosion.

COMPUTER AND INFORMATION SCIENCES

Feedback Control Theoretic Methods for Learning and Adaptation in Multiagent Systems - Professor Jeff Shamma of University of California at Los Angeles (UCLA)was awarded a new grant to develop feedback control theoretic methods for learning and adaptation in multiagent systems and to investigate their potential as analysis and design tools for complex adaptive systems. His recent work at UCLA has made a major breakthrough in the game theoretic framework of distributed learning. This new work considers adaptation methods for the strategies of distributed agents, each with private utilities/intentions. It is anticipated that this work will lead to a significant new theoretical understanding of complex system behavior, analysis, and ultimately design.

Self-directed Intrusion Detection – (Professors Paul Barford and Somesh Jha, University of Wisconsin, Madison) - Today's users of the Internet and the network infrastructure are threatened by the ever increasingly sophisticated attacks and malicious network traffic. On the other hand, current generation of intrusion detection systems (IDS) suffers from high false alarms and from its incapability of detecting new attacks in real time. Professor Barford and Professor Jha have recently developed new technology that addresses the false alarm problems (both positive and negative) in IDS. The

investigators will implement a hardware based real-time IDS node that can be deployed in the wide area self-directed IDS.

Computer Security Risks Due to Exploiting Microprocessor Power Dissipation – (Professor Kevin Skadron, University of Virginia) - Malicious users may potentially manipulate the micro-processor that leads to over consumption of power, heat build up, severe energy drain, and voltage in-stability. The risks associated with such "power exploits" are poorly understood. Professor Skadron is currently studying the feasibility of such attacks. His research will characterize the different types of attacks and their potential harm. Further the research will identify the distinguishing features that can be used both to determine when a system is under attack by some form of power exploit and to guide future designs to reduce their intrinsic vulnerability.

Membership Control in MANETs and Peer Groups – (Professor Gene Tsudik, University of California, Irvine) - Membership control in MANETs is important to future tactical communication networks which have the unique characteristics of high mobility and dynamic changing user community. Professor Tsudik is developing a framework that supports member admission and member revocation for dynamic MANET groups. The framework will contain membership control attributes and policies. The membership control policies are enforced through cryptographic mechanisms.

Application of Intelligent Agents – Intelligent Agent (IA) technologies are key to achieving significant improvements in functionality for signal/data/information-intensive systems. These technologies are expected to enable advances in a wide variety of decision-support and situation-monitoring oriented applications. IA technologies are key to implementing high-level "information-fusion" capabilities, and effectively dealing with massive amounts of heterogeneous, and often distributed information. A principled approach to this concept allows for the rapid construction. At present, the Army is building a "Strategic Readiness System" (SRS) to be used by Army leadership to enhance the management of organizational and soldier/unit resources. A Phase I Small Business Innovative Research (SBIR) project titled "Intelligent Force Management" is now being initiated. This SBIR topic is centered on Intelligent Agent Technologies and information-fusion.

Extended Finite State Machine Representation - Research on "Extended Finite State-Machine" representations are being used to help extract reasonable interpretations of text documents. This research, coupled with the natural language expertise, at the University of Pennsylvania (UPenn.) is now being applied to the interpretation of blood-bank management regulations and policy documentation. This is a joint effort by DOD Defense Blood-Bank Standards System (DBSS), FDA, and UPenn. Several joint papers have been published and there is reasonable expectation that this technology will contribute to significant improvements in the management and assessment of policy compliance issues. As importantly, this technology is expected to contribute to the support for improving system/software engineering capabilities for the elicitation, validation, and refinement of system requirements and engineering system support.

High Confidence Embedded Systems - ARO is collaborating with NSF and FDA to transition recent advances in system/software engineering capabilities to industry. The "High Confidence Embedded Systems" (HCES) research initiative, sponsored by ARO involves three teams of investigators; the three teams of researchers are at the University of Pennsylvania, Carnegie-Mellon University, and Kansas State University. The HCES researchers and other ARO sponsored researchers have a number of ongoing interactions with industry to improve the design capabilities for safety-critical systems. This work has direct connections to the Army combat casualty care interests, and previous ARO sponsored research on an infusion-pump for combat soldier care. The latest in series of workshops with industry was held in November 2004. Participants included a number of scientists from government agencies, industry, and academia.

Congestion Control for Sensor Networks – (Professor Andrew Campbell, Columbia University) - In the current proposed designs of sensor networks, the sensors near the gateway will have an inequitable power drain, since they will be need to forward the data for all of the sensors that are farther away from the gateway. Also, there will be significant congestion in sensor network around the gateway when an event causes many sensors to transmit. Professor Campbell will be developing an architecture to combat the congestion near the gateways under this grant. This architecture will include receiver based congestion detection, hop-by-hop backpressure, sink-to-multi-source regulation, and virtual sinks.

Multiframe Image Deblurring and Superresolution - (Professor Nirmal Bose, Pennsylvania State University) - The primary goal of next year's research will be to perform satisfactory multiframe deblurring in the Second Generation Wavelets (SGW) super-resolution framework with, initially, known blur support, and, subsequently, unknown blur support. A secondary goal will be to investigate optimal trade-off between reconstruction quality and compression rate using SGWs not only for imagery but also for speech in multimedia applications.

ELECTRONICS

Uncooled Tunable LWIR Microbolometer – Multi- or hyper- spectral images contain much information that can be used to reduce clutter and enable aided target recognition. However, the extra information in a large number of spectral bands makes signal processing complex and difficult for real time operation. In most situations, only a few (< 10) spectral bands are important, but the particular spectral bands may differ depending on the background environment and target type. Professor Joey Talghader, at the University of Minnesota, is designing and fabricating an uncooled infrared detector that can be tuned using a MEMS Fabry-Perot cavity placed in front of the detector. This will allow the focal plane array to be tuned on a pixel by pixel basis to match the environment with a sensible number of spectral bands for real time image analysis. In this work, Professor Talghader is concentrating on a proof-of-principle, single pixel, demonstration. Two designs will be covered. The first will employ a standard

microbolometer with a separate micromachined Fabry-Perot etalon above the pixel to select various spectral regions. The etalon will be composed of a single layer of high-index material with an air gap above a high index substrate. The second design will integrate an optical cavity into the microbolometer detector. In this design the microbolometer itself will serve as one of the etalon mirrors as shown in the sketch below. Both designs will be spectrally tunable and contain a broadband operation mode. This is an initial seed-project that is co-funded with DARPA to show feasibility of spectral tuning an uncooled IR pixel.

Microbolometer

Air Gap (n = 1.0)

Metal Vias

Control Electronics

Silicon Substrate
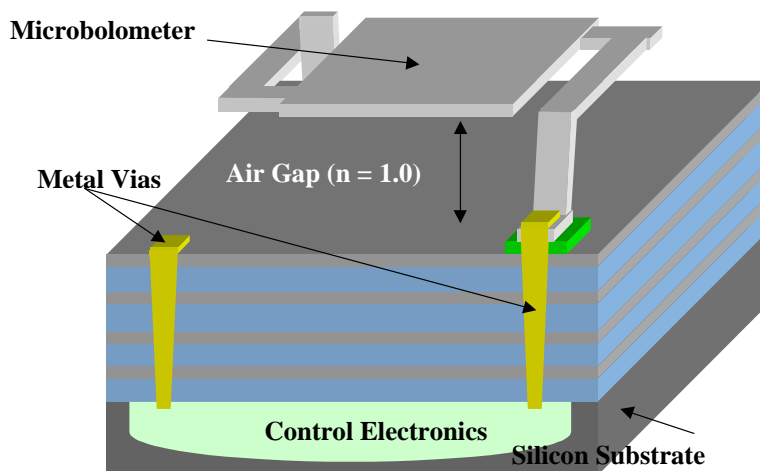
Figure 1. Spectrally tunable IR detector with integrated microbolometer.

Magneto-optic Properties of III-TM-N Nanostructures – Professor C. Abernathy and her research group at the University of Florida are investigating the effects of quantum confinement on the magneto-optical properties of III-TM-N layers. Synthesis of these materials has been carried out both by ion implantation and by molecular beam epitaxy. These materials show evidence of ferromagnetic ordering at room temperature, suggesting Curie temperatures well above those found in the more widely studied materials such as GaMnAs. Reduced dimensionality is being explored to enhance the magneto-optical behavior for device applications. In general, quantum-confined crystals have shown improvements in the magnetic properties over thin film or quantum well counterparts. GaMnN nanowires with diameters in the range of 25 - 75 nm have been reported which show room temperature ferromagnetism and higher coercive fields than for thin films. Reduced dimensionality can also affect the dynamical properties such as carrier and spin-relaxation. Using e-beam lithography and plasma etching, arrays of nano-pillars will be formed in III-TM-N thin films. Temperature dependent superconducting quantum interference device measurements will be made to assess the magnetic properties. Optical laser excitation will be used to examine spin-polarized light emission from the nano-pillars. Results of this research will determine the benefits of reduced dimensionality on spintronic devices and heterostructures.

Eye-Safe Light Emitters Based on Newly Developed GaAsSbN Quantum Wells - Professor Shanthi Iyer, at North Carolina Agricultural and Technical State University, is developing quaternary diluted nitride quantum wells grown on GaAs under a program jointly funded by ARO and the Missile Defense Agency. The wavelength range for these materials has been exteneded into the eye-safe region of 1.5 microns and beyond for application to many Department of Defense programs. Light emitting diodes and possibly laser diodes are now ready to be attempted and processing in underway with a collaboration at North Carolina State University. Professor Iyer's group has been growing these molecular beam epitaxy based materials for the past three years and has successfully obtained room temperature photoluminescence at energies as low as 0.81 eV (1.54 micron) and hopes to extend this even up to 2 microns. This quaternary system is more attractive than other dilute nitride systems as it allows independent variation of the band offsets and the lattice constant of the host material. NCA&T is a historically black university and has received this funding through HBCU programs at MDA and through optoelectronics program management at ARO.
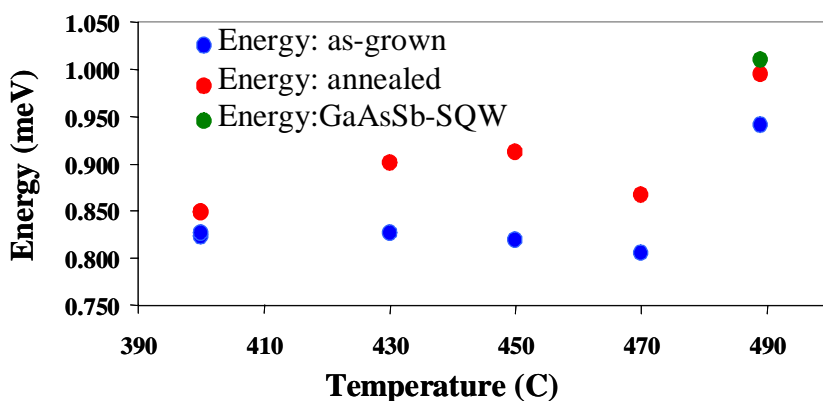
Figure 2. Photoluminescence energy vs. growth temperature for MBE grown GaAsSbN quantum wells with 0.7-1.5 % Nitrogen.

Photonic Control of Bio-Molecular Electronic Components - The rapidly developing field known as nanotechnology suggests that there is a vast potential for revolutionizing electronic systems as they are known today. The possibilities for enormous increases in functionality, integration and speed offered by molecular-level systems have motivated a detailed investigation of nanoscale elements and components. One specific avenue for realizing the technological payoffs available at the nanoscale is to incorporate aspects of architecture and algorithmic functions that already exist in nature. Research at the University of Virginia (Professor Boris Gelmont) has recently demonstrated that the unique spectral emission/absorption properties of biological (bio)-molecules at terahertz (THz) and optical frequencies potentially offer a completely new paradigm for realizing highly controllable algorithmic function and communication within densely-packed molecular systems. This research has developed new models and utilized them to predict how the THz spectral characteristics of small isolated bio-molecules change under excitation from ground-state to metastable-states. This work is being expanded to consider larger and more complex bio-

molecules that are bound to metal/semiconductor interfaces. Here, the computational challenges of modeling coupled bio-molecular systems are being addressed through collaborations with North Carolina State University (Professor Timothy Kelley) that will work to enable advanced parallel algorithms and simulation tools. This research is significant because it will establish the scientific insights for defining a completely new paradigm in nanoelectronics with the potential for leading to a new class of integrated *Bi-Molecular Electronic Architectures* that can be used effectively for the *Sensing and Processing of Bio-Signatures*.

Integrated Nanoscale Semiconductor-Biological Systems – At the present time, Nanoscience is advancing at a dramatic pace and is making revolutionary contributions in diverse fields including electronics, optoelectronics, quantum electronics, materials science, chemistry, and biology. Of particular importance and relevance, semiconductor quantum dots may now be fabricated with nanoscale dimensional features portending the direct integration of such semiconductor nanostructures with biological structures. Furthermore, a host of recent advances in bio-science suggest many practical and important uses of semiconductor nanostructures integrated with biological structures. For example, peptide-based binding of nanoscale electronic and optical components directly with nerve cells and other biological systems appears extremely feasible in the future. These facts have motivated the support of new research at the University of Illinois at Chicago (Professor Michael Stroscio) that is investigating the binding of a variety of different semiconductor nanostructures, including quantum dots, with biological structures. Hence, this research is establishing a technology base for a completely new strategy for realizing integrative semiconductor-biological systems**.** For example, techniques are being developed where layer-by-layer biomolecule-based chemically-directed assembly of ensembles of semiconductor quantum dots can be achieved. Hence, this research is advancing towards a new electronic regime where terascale electronic integration with biomolecular links is feasible. Therefore, such integrated semiconductor-biological system will be a new avenue to numerous forefront applications including: molecular electronic systems for information processing; new classes of information processing devices; establishing electrical interfaces with neurons at locations determined with nanoscale precision; control of biological functions such as the gating of ion channels; and possibly electrically- and optically-based prosthetics that signal and control cells directly as well as neuronal memory devices**.**

Terahertz Frequency Electronics for Remote Sensing and Imaging - Innovative research both in fundamental sensing science and in very high frequency electronic technology is establishing a foundation for a future terahertz-frequency spectroscopic-based approach to threat agent detection. The last research frontier in high-frequency electronics now lies in the terahertz (or submillimeter-wave) regime between microwaves and the infrared (i.e., 0.3 – 10.0 THz). While the terahertz (THz) frequency regime offers many technical advantages (e.g., wider bandwidth, improved spatial resolution, compactness), the solid-state electronics capability within the THz frequency regime remains extremely limited from a basic signal source and systems perspective (i.e., on the order of milliwatts or below). However as we enter the new millennium, important applications of THz technology are rapidly emerging that are extremely relevant to national defense. Pioneering research is currently under support that is investigating the

scientific issued related to spectroscopic sensing and imaging along with a significant investment towards the advancement of transmitter and receiver technology for remote detection. Multiple programs jointly led and supported from ARO, ECBC, DTRA and DARPA are investigating fundamental processes associated with chemical and biological agent detection and the phenomenology of imaging of explosives, weapons and other threats. Here research efforts and collaborations between academic institutions (e.g., University of Virginia, University of California at Santa Barbara, Ohio State University and others), government laboratories (e.g., JPL, ECBC, NGIC and others) and industry (e.g., Goodrich Optical Division, Virginia Diode Inc., Picotronix Inc. and others) are rapidly expanding our understanding of the sensing science and capabilities of state-of-the-art technology at terahertz frequencies. These advances will soon enable a number of important practical demonstrations which can be expected to include the generation of THz signatures for live anthrax, the remote spectroscopic detection of spore clouds, along with the short-range imaging of concealed explosives and weapons.

Circuit Calculators for Handheld Computers – Develop a new generation of RF and microwave circuit CAD tools operating across a wide range of computing platforms including handheld and portable computers. Dr. David Rutledge at the California Institute of Technology, the PI on this effort, was an author of Puff, one of the first available visual microwave design tools. Since its creation in the 1980's it has sold over 30,000 copies to individuals, companies, and institutions. Dr. Rutledge and his group will use modern programming concepts and tools to develop and extend the capabilities of an RF and microwave circuit calculator CAD tool. In the process, they will discover and refine new methods for creating, organizing, storing, and using RF and microwave components to build simulations. The resulting CAD tool will be tested in a microwave engineering class, and feedback from the students will be used to optimize the user interface, data visualization and control, and data output capabilities.

Development of Vector Parabolic Equation Technique for Propagation Prediction in Urban and Tunnel Environments – The proposed research will provide the capability to accurately predict radio wave propagation in urban outdoor and tunnel environments for mobile wireless communications, including higher order effects such as multipath effects, path loss, angular spread, and delay spread, using 3D parabolic equation methods. Dr. Janaswamy at the University of Massachusetts Amherst, the PI on the proposed project, is a pioneer in the development and extension of the parabolic equation method. The proposed research will extend this important calculation technique to three dimensions, enabling it to calculate complex higher order propagation effects important to characterizing high data rate mobile wireless communications channels. The parabolic equation method is complementary to existing 3D techniques based on ray tracing methods, particularly for urban terrain and other complex, restricted environments. Radio wave propagation prediction techniques for the determination of path loss, angular spread, and delay spread for mobile wireless communications will be developed. The resulting methods and techniques will be applied to several situations including uneven terrain and polygonal buildings for the urban outdoor environment and a variety of cross sectional shapes such as rectangular and arch-shaped for the tunnel environment. The

simulation results will be verified and validated using outdoor measurements of the campus environment and path loss measurements in the storm drains and steam tunnels on campus.

ENVIRONMENTAL SCIENCES

Atmospheric Sciences - Recent success in acoustic tomography of the atmospheric surface layer, specifically progress in design of a sampling array, development of timing of signals across the network and purchase of instruments and equipment has set the stage for field studies to measure temperature and wind within a volume of the atmospheric surface layer. This lower 30m of the atmosphere exchanges energy and momentum between the ground and the air. The parameterizations of surface layer processes used in forecast models which provide key factors used to assess Army weather capabilities, do not perform with skill. Measurement of the wind and temperature at this scale will significantly help performance of small scale weather models, dispersion of aerosols and gases (CB defense), and performance of acoustic systems operating near the ground. This is in the primary part of the atmosphere where soldiers operate.

Terrestrial Science - The current ARO Terrestrial Sciences basic research investment related to terrain analysis will develop, validate, and apply new techniques for multi-image road extraction. Research in landmine detection should lead to the development of a non-contacting acousto-optic approach to landmine detection as well as new adaptive detection and classification algorithms for multi-modal inverse problems for obscured ground targets, landmines, and subsurface structures which will be based upon both physics-based approaches that use the a fundamental wave equations and statistically physics-based methodologies that use of forward algorithms and available measured data for training statistical models. Atmospheric icing research is examining the physical properties and microstructure of the natural ice forms that on solid surfaces under atmospheric conditions to provide the foundation for the development prevention and amelioration technologies. Hydrologic research will provide the US Army Corps of Engineers with an understanding of the hydrologic behavior of watersheds that experience both saturation-excess and infiltration-excess runoff production mechanisms in extreme climate environments at different times of year and under different rainfall regimes. It will also provide new modeling and simulation capabilities for groundwater flow and transport modeling for environmental remediation. Research on coastal sediment transport will provide new knowledge and understanding of the geology underlying a beach controls the development, shape, and movement of sandbars in the surf zone as well as its stability over time. Other Terrestrial Sciences research will lead to improved process models for mobility prediction and improved land management tools and decision aids for the sustainable use of Army training and testing lands.

LIFE SCIENCES

Biowarfare Countermeasures - A large effort is currently focused on the development of countermeasures to biowarfare agents, such as viruses, bacteria, fungi, and toxins. The goal of this research is to neutralize the attractiveness of this type of weapon for an enemy nation or terrorist. One approach uses natural enzymes produced by bacteriophage, bacterial viruses that infect and explode bacterial cells. These enzymes are highly specific and work equally effectively on wild type bacteria and bacteria genetically engineered to be antibiotic resistant. Research funded by ARO at Rockefeller University is using the anthrax specific bacteriophage enzyme to develop therapeutics for humans exposed to anthrax. Another example is research funded at the Mayo Clinic to develop a high performance supercomputing approach to identifying protein structure and small molecules that can neutralize essential proteins in biowarfare agents. This approach has already been demonstrated to be rapid and effective at identifying countermeasures to specific threat agents. A third example is collaboration between Coley Pharmaceuticals and Bioport Inc. to improve the anthrax vaccine by adding immune stimulating oligodeoxynucleotides. Benefits of increasing the effectiveness of the anthrax vaccine include reducing the number of injections required to achieve protection, reducing the length of time required before troops are ready, increasing the number of doses available, reducing the potential for side effects, and increasing the acceptability of this vaccine to troops and civilians.

Soldier Performance – ARO is currently working with DARPA on a large phase II program to identify mechanisms to improve soldier cognitive performance during extended periods of sleep deprivation. Soldiers that are sleep deprived for 24 hours function at the same cognitive level as a legally drunk individual, however they are unaware of their cognitive inhibition. Soldiers, as well as others such as pilots and medical personnel, are often sleep deprived for extended periods of time. This program seeks to identify the molecular basis of sleep deprivation, and to identify novel, non-invasive therapeutics to counteract the cognitive decline observed in sleep deprived individuals. Extensive work characterizing the molecular changes has already been done in well-established model organisms, including the mouse, bird, and fly. Work is also being performed to identify the mechanisms that enable some species of birds to stay awake with no cognitive impairment for up to two weeks, and how dolphins, other marine mammals, and birds can have one brain hemisphere asleep while the other is awake, alert, and functioning at full cognitive capacity.

ARO is working on a second program to develop better pain therapeutics. The current standard for pain medication has negative effects on the nervous system, respiratory system, bowels, and kidney function, resulting in significant impairment of the soldier's alertness, judgment, and cognitive and physical performance. Other side effects include nausea, vomiting, respiratory depression, renal colic, and confusion. The individual's response is not predictable, and not only is the soldier unable to function, but further personnel must be devoted to monitoring the soldier's vital signs. Rinat Neurosciences, in a $929K phase II effort, is developing a novel pain therapeutic, based on antibody interference to the pain pathway. Preliminary work indicates that a single treatment is

effective for 2 to 6 weeks, has no effect on mental performance, physical performance, or sensitivity to external stimuli, and has similar effectiveness levels to currently used pain therapeutics.

Environmental Remediation – A lot of progress has been made during 2004 for new, highly specific and effective procedures for degrading recalcitrant environmental contaminants such as TNT (trinitrotoluene), TCE (trichloroethylene), etc., found in high soil concentrations in sites around the country. Some of this work in the past was in enzymology (University of Iowa) or genetics (University of Idaho and Yale). However, work in the laboratory did not always translate to the field, so new techniques were sought. One new area is the use of biofilms. Work at Montana State and in two new STTRs (both of which were chosen for Phase 2 work) is looking at the role of biofilms in remediation. There has been real progress this past year, and we look for a real breakthrough in the near future. Also anticipated for results next year, is the use of biofilms to monitor municipal and/or military water supplies for biological or chemical weapons.

Bacteriorhodopsin-based Optical Memory – New SBIRs are in the process of being chosen in the field of "Innovative Hosts for Bacteriorhodopsin-based Optical Memory". The top two look very promising and probably will have some accomplishments to report next year.

Exploiting Biotechnology Opportunities for the Army – It is anticipated that great strides in the area of bioengineering sciences and its potential for application to groundbreaking biotechnology for the Army of the future will be made over the next year within the Army's newest University Affiliated Research Center, the Institute for Collaborative Biotechnologies (ICB). The inspiration for the ICB comes from the fact that biology uses precise mechanisms to produce exquisitely structured materials, and that coordination of biological function at the molecular, cellular and systems level takes place by remarkably effective communication and information transfer. The promise here is for providing unique enabling technology for more advanced integrated circuits for high-performance sensing, computing and information processing, and actuation than are used in existing manufacturing. This synthesis of high performance materials is accomplished with a precision of nanoscale-architectural control that exceeds the capability of current engineering, particularly in the designing and sculpting of materials in three-dimensions. Likewise, the integration of component function in biological systems is astonishing, so the lessons learned here are sure to have strong impact on engineered information processing systems integration as well. The idea is to understand biological mechanisms and to harness them for design and fabrication of new materials, devices and systems performance to equip the Army of the 21st century. But the benefit to the United States is more than military. The for-profit industrial partners have the opportunity and the incentive to translate to the civilian marketplace the fruits of the research findings.

Closely related to the above promise of anticipated accomplishments from the ICB, Professor Angela Belcher, an ARO PECASE single investigator previously at University

of Texas now at Massachusetts Institute of Technology (MIT), and leader of the MIT partnership within the Army's newest UARC, the "Institute for Collaborative Biotechnologies" (ICB), has developed a virus-based scaffold for the synthesis of single-crystal ZnS, CdS, and freestanding chemically ordered CoPt and FePt nanowires, with the means of modifying substrate specificity through standard biological methods. Peptides (selected through an evolutionary screening process) that exhibit control of composition, size, and phase during nanoparticle nucleation have been expressed on the highly ordered filamentous capsid of the M13 bacteriophage. Removal of the viral template by means of annealing promoted oriented aggregation-based crystal growth, forming individual crystalline nanowires. This exploitation of the self-assembly motifs employed by the M13 bacteriophage to produce a biological scaffold provides a means of generating a complex, highly ordered, and economical template for the general synthesis of these single-crystal nanowires. By introducing programmable genetic control over the composition, phase, and assembly of nanoparticles, a generic template for the universal directed synthesis of a variety of semiconducting and magnetic materials can be realized. The unique ability to interchange substrate specific peptides into the linear self-assembled filamentous construct of the M13 virus introduces a material tunability that has not been seen in previous synthetic routes. Modification of biological systems by the introduction of substrate-specific peptides presents a means of achieving well ordered nanomaterials in a cost-effective and scalable manner, impacting the availability of unique electronic, magnetic and optical materials for Army use in advanced component structures for faster, smarter, and lighter sensing, targeting, and other forms of information processing devices

Neuromorphics and Neuroergonomics - Recent advances in the understanding of neurophysiological mechanisms used in nature to control movement and process sensory inputs has opened the field of computer circuit design beyond the digital revolution. Nature uses analog type structures to produce small and highly efficient pattern generators, shape and movement detectors and feedback systems that digital systems have great difficulty emulating efficiently. Several projects in Life Sciences touch on the fields of neuromorphic (nervous system-like) and neuro-ergonomic (designed to interface well with the human nervous system) design. Transitions to be expected include the creation of a neuromorphic circuit design that will control a powered lower limb prosthesis that will permit normal walking through the implementation of analog reflex arc commonly seen in the nervous system. Other projects include workshops in neurocognitively adaptive display designs that use non-invasive sensing methods to modulate information displays so as to best match the abilities and desires of the human using them. Automated target detection also is benefiting form the approach by using approaches common to living visual systems, e.g. center-surround organization of visual search fields and saliency based potential target location determination. The concept is not limited to vision and locomotion - advances in the understanding of how bats modulate and process their sonar chirps has resulted in patent filings for biologically inspired algorithms that optimize signal/noise ratios and range/resolution tradeoffs in future sonar design. Other work in olfaction is leading to advances in learning how animals fuse odor and local wind data to navigate efficiently to an odor source. These

concepts may lead to more efficient robot designs for detecting and finding chemical leaks in complex urban environments.

MATERIALS SCIENCE

High Spatial Resolution Mapping of Water in Hydrated Polymers - The Libera group at the Stevens Institute of Technology has conducted research on the development of spatially-resolved electron energy-loss spectroscopy (EELS) in the scanning transmission electron microscope (STEM) for studying the morphology of engineered polymers. Recently, their focus has moved from dry polymers, mapping the curing-agent distribution within the interphase in epoxy-matrix composites (work accomplished in collaboration with Dr. Steve McKnight, Army Research Laboratory, Aberdeen) to mapping the morphology of solvated polymers. This is a new and unique application of the TEM. The broad goal is to relate solvent distribution to the underlying polymer morphology, and there are many DOD/civilian applications where controlling the solvent distribution in a complex polymeric solid is critical to success. To date, their EELS spectra show that they can spectroscopically differentiate between Nafion, water, and DMMP, an organic solvent used to simulate sarin nerve agent. They have also demonstrated that they can prepare, image and study robust and relevant specimens of both dry Nafion and frozen-solvated Nafion saturated with DMMP. To our knowledge, this is the first cryo-STEM image of a solid polymer solvated with an organic solvent and is in itself a nice achievement. Using EELS, they have shown that the average thickness change upon *in situ* DMMP drying corresponds roughly to the bulk weight change measured at Natick. Significantly, the solvated specimen shows regions with bright contrast not seen in the dry specimen, and it is anticipated that they will soon be able to determine the nature of these features using spatially-resolved spectroscopic techniques.

Low Loss Iron Films at Microwave Frequencies - The reduction of GHz damping in metallic ferromagnetic systems is a critical need. Recent electronic structure calculations (spin-polarized relativistic KKR) predict that additions of vanadium to iron will lower the magnetic anisotropy energy of the alloy to values near zero, which should lead to significantly lower microwave losses. In the coming year researchers at Columbia University will be preparing thin iron films containing small amounts of vanadium and confirming that they can indeed deliver superior microwave properties.

Novel Energy-Absorbing Porous Composites - Researchers at the University of Akron are expected to demonstrate an innovative energy absorption phenomenon for advanced protective materials. The fundamental basis for the effort stems from the observation that, when a non-wetting liquid is forced to flow into porous materials under external pressure, the high surface-to-mass ratio causes a large amount of energy to be transformed into solid-liquid interfacial tension. While this phenomenon has been utilized considerably for catalysis and selective absorption applications, the proposed effort seeks to explore its effectiveness for high strain-rate mechanical protection systems. Dynamic experiments will be carried out to study the effects of the particle/pore

size, particle/pore volume fraction, and interfacial tension. The research offers the potential to establish a new methodology for lightweight armor materials design.

Advanced Methods for Field Assessment of Hydrogen Damage – (Professor David Olson, Colorado School of Mines) - Hydrogen easily dissolves in steels during processing, welding, and corrosion. This dissolved hydrogen dramatically affects the mechanical behavior, lowering the fracture toughness and often leading to catastrophic failure in service. For this reason, processing procedures take great care to control the amount of introduced hydrogen. This is particularly true in welding, where practices rely on the certification of a weld process, and the certification of the operator, along with periodic destructive examination of standard test coupons for quality assurance. Often, processing conditions are dramatically different from the ideal conditions used for process design or certification. This leads to uncertainty in the product, which designers mitigate by using large design factors of safety and generally over-designing the system. The need for high performance, lightweight systems and the frequent specification of modern high strength steels makes this mitigation technique less feasible. The group at Colorado School of Mines has been exploring a new technique for hydrogen detection. The aim of
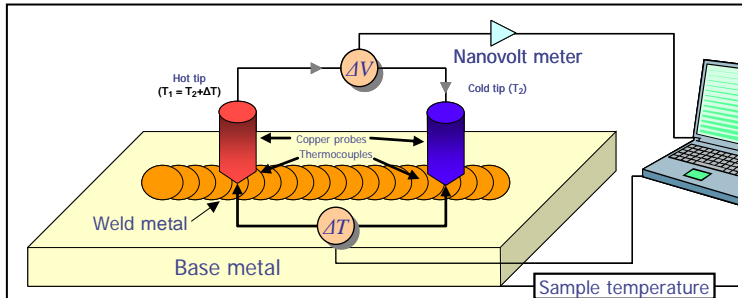
A schematic diagram of the Seebeck measurement system (above). Typical measurement of thermoelectric power for steel weld beads with and without hydrogen (below).
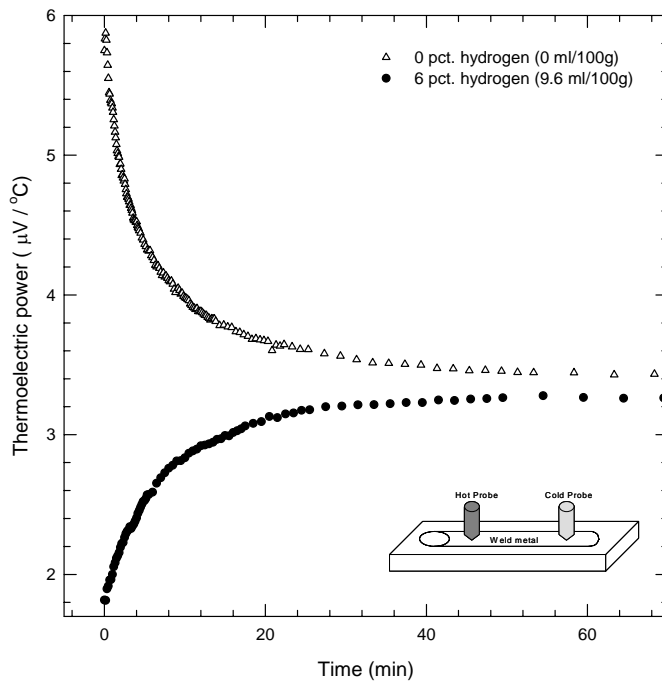
the project is to measure the amount of local hydrogen in a rapid test using a small probe. The technique they have settled on uses the thermoelectric effect. They measure the Seebeck coefficient, which is a measure of the thermoelectric power, using a simple two-

point probe attached to a small computer. Changes in the Seebeck coefficient reflect changes in dissolved hydrogen, allowing the probe to be a fast screening tool suitable for shop floor or field uses.

MATHEMATICS

Stochastic Optimal Control Algorithms and Next Generation Technologies for Dynamic Resource Allocation in Mobile Communications Networks – (Scientific Systems Company, Inc.) - In both the United States and overseas, radio spectrum is a tightly controlled commodity, with regulatory agencies assigning spectrum bands for the various service types. Since the amount of usable spectrum is finite, as more services are added, there will come a point at which spectrum will no longer be available. On the commercial side, the rapid proliferation of wireless devices and their increasing sophistication and bandwidth usage is bringing us close to such a time. On the military side, the growth in the number of types of devices and transmission modalities is exacerbated by the Armed Forces transition to Network Centric Warfare, which aims to digitize the battlefield. Digitization requires the rapid transmission of large amounts of information over significant distances, creating an explosive demand for bandwidth. As an example of this phenomenon, it is reported that Operation Iraq Freedom is utilizing 42 times more bandwidth than the bandwidth utilized during the 1991 Gulf War. Another difficulty associated with spectrum utilization is the issue of deployment. Currently, extensive, frequency by frequency, system by system coordination is required for each country in which wireless devices are operated. As the number, size and complexity of operations increase, the time for deployment is becoming unacceptably long.

While it is true that new technologies such as ultrawideband transmission and smart antennas are alleviating the issue of spectrum scarcity, and more flexible policies allowing for spectrum leasing and reallocation are facilitating deployment, it is recognized that these problems are not going to go away in the near future. This is especially true for military systems, where the demand for bandwidth is expected to far surpass its availability in the next decade. Both the scarcity and the deployment difficulty problems are a result of the static nature of current allocation policies. This approach lacks the flexibility to aggressively exploit the possibilities for dynamic reuse of allocated spectrum over space and time, resulting in apparent scarcity. It also mandates a priori assignment of spectrum to services before deployment, making actual deployment difficult.

Preliminary data collected by the FCC in the United States and by others in Europe have indicated that large portions of allotted spectrum are unused. That is, there are a number of instances of assigned spectrum that is used only in certain geographical areas, and a number of instances of assigned spectrum that is used only for brief periods of time. This wastage is expected to increase in the future, both spatially, due to the increasing localization of propagation due to devices moving up in frequency, and temporally, due to increase in services having a highly bursty nature. The objective of this R&D program led by Scientific System Company with the participation of BBN Technologies and

academic partners is to develop a rigorous mathematical formulation for dynamic spectrum allocation and to design communications protocols and distributed resource allocation algorithms to enable dynamic spectrum allocation on mobile wireless networks. We view the allocation of spectrum to users as a stochastic control problem with coloring and fairness constraints. Recent developments in distributed stochastic systems will be used to derive computationally efficient allocation policies.

The resulting algorithms will be implemented and tested on realistic, high-fidelity simulation environments, representing mobile networks with increasing degrees of complexity. The effort will build upon pioneering work by BBN Technologies under DARPA's Next Generation Communications program (XG program), which has developed a comprehensive framework for the design and deployment of communication devices capable of dynamic spectrum allocation. Besides BBN, our research team includes Professor Harold Kushner from Brown University, and Professor Sanjoy Mitter from Massachusetts Institute of Technology, world renowned researchers in Stochastic Control and Communications Theories.

The effort at hand is a combination of an important class of applied mathematics problems on one side, related with the optimal allocation of resources, and the looming spectrum bottleneck faced by the Army and the commercial sector on the other side. The application of sound theoretical and algorithmic techniques to the dynamic spectrum allocation problem is expected to allow vastly better resource allocation and utilization, leading to significant improvements in network performance.

Modeling and Analyzing Terrain Data by Modern Mapping Techniques – (Pankaj Agarwal and Lars Arge, Duke University) - Terrain analysis is an integral part of the military intelligence preparation of the battlefield, commonly used to support both defensive and offensive operations. It consists of interpreting natural and manmade terrain features, together with the influences of weather, to determine their effects on military operations. In addition to military applications, terrain analysis also provides the foundation for a wide range of critical civil and environmental engineering tasks in natural disaster management. In recent years, the potential of terrain information systems has been greatly enhanced by new terrain mapping technologies that are capable of acquiring millions of geo-referenced points within short periods of time. However, while acquiring and geo-referencing the data has become extremely efficient, transforming the resulting massive amounts of heterogeneous data to useful information for different types of users and applications is lagging behind. The objective of this research is to provide enhanced terrain modeling and analysis capabilities by developing sophisticated algorithms that function with massive non-standard datasets, such as point-clouds, and that produce a confidence level for the results. The expected outcome of this research includes: (1) Robust, memory-aware, and efficient algorithms for hierarchical 3D digital models of terrains from data acquired by recent mapping techniques, which can rapidly update the model as new data arrives; (2) Simple, memory-aware, and efficient techniques for watershed, mobility, and line of sight analyses on grid as well as TIN (triangulated irregular networks) models; and (3) Implementation of selected algorithms into open-source GIS (geographical information systems).

ANTICIPATED ACCOMPLISHMENTS

Data Fusion in Large Arrays of Microsensors (Sensorweb) – (Alan Willsky, Massachusetts Institute of Technology) - The team for this Multidisciplinary University Research Initiative will integrate the results obtained recently (distributed, "particle"-based algorithms for localization in sensor networks, a scalable, communication- and power-sensitive, message-passing algorithm for distributed data association, sparse signal reconstruction, fast methods for computing information-theoretic quantities for data association and target discrimination, information-theoretic methods for intelligent sensor querying and "negotiated network formation") into a theoretical framework for data fusion in large networks of acoustic, seismic, electric-field, magnetic and other "myopic" sensors with strong constraints on power and communication.

Accurate, Data-Compressed Representation of Terrain by L_1 Splines – (John Lavery, Army Research Office, and Shu-Cherng Fang, North Carolina State University) - Preliminary evidence indicates that, in both the non-parametric case and the parametric case, first-derivative-based univariate L_1 splines provide further improvement vs. the already known good shape preservation capabilities of second-derivative-based univariate L_1 splines. A framework for first-derivative-based univariate L_1 splines will be completed. Parametric versions of both second-derivative-based and first-derivative-based univariate L_1 splines will be developed and the shape preservation capabilities of parametric second- and first-derivative-based univariate L_1 splines will be compared. The current compressed primal affine algorithm for calculating L_1 splines has performed well but is not always able to achieve a duality gap close to machine zero, especially for large data sets. Since primal-dual methods tend to have greater robustness than primal affine methods, a compressed primal-dual method will be developed and will be compared with the current primal affine method.

Swarming in Two and Three Dimensions – (Andrea Bertozzi, University of California at Los Angeles) - The models of swarming based on bio-sociological principles (rather than artificial principles, often those from fluid dynamics) that are being developed by this project will be ported onto teams of mobile robots for physical experiments in a laboratory. The teams under investigation will have tens of robots, which is a range that is of practical interest to the Army.

PHOCI : Photonic Communications Imager – (Dale Martin, Clifton Labs) - The PHOCI optical imaging system, which does both image capture and transfer of data, will be field-tested in a factory environment with non-optimal optical transmission..

Coarse-to-Fine Computational Vision – (Professor Stuart Geman, Brown University) - Machine vision is now routinely used in industrial automation. Existing systems for object recognition read or verify characters and information symbols robustly and at high speeds on ordinary hardware platforms. But performance often degrades in uncontrolled environments and in searching for multiple and varied objects and relationships among them. The goal of this project is to formulate the recognition problem more globally, as one of scene analysis rather than object detection and identification, and thereby to accommodate the background structures and object variability that confuse today's state-of-art systems. To achieve this goal, two candidate frameworks for full-scale scene

interpretation will be studied. These frameworks address complementary issues in machine vision, but are linked by a central role for coarse-to-fine computation. Prototype systems, possibly involving a hybrid algorithm drawing from each of the two approaches, will be implemented.

Modeling Deformations and Contacts – (Leonidas Guibas and Ronald Fedkiw, Stanford University) - The objective of this research is to study and develop computational algorithms for simulating multiple deformable and rigid objects in close contact. Deformable objects of particular interest include clothing and fabric, and human tissue and limbs. Examples of close contact situations to be considered include fabric draping over rigid objects, and the interaction of clothing and human models. Past research on deformable objects has concentrated on either very rigid solid materials such as metals or completely non-rigid materials such as fluids. Very little research or techniques have been developed to model "soft" materials such as cloth or fabric. This effort seeks to fill that gap and is of significant value to a number of Army and civilian applications. It is anticipated that such research will lead to improvements in modeling capabilities for use in training simulators and in product development and testing and will enhance the development of soldier clothing and equipment.

Networking Research: Analytical Theory of Protocols – (John Doyle and Steven Low, California Institute of Technology) - This project has as its goal to fill out the theoretical details of a unified theory for network coding and congestion control. The project will focus on three issues: (1) a source/channel "mice/elephant" (= statistically long-tailed, not Gaussian) description of WWW and Internet traffic, (2) a duality theory of decentralized resource allocation, and (3) a robustness and stability theory for the dynamics of traffic control protocols and automatic queue management. The results of this research will allow integration of layers complex large-scale networks. The motivation for the project is an observation that networks are robust (in a small range of behaviors) yet fragile (globally) and that network traffic is self-similar (long-range time-dependent). This work is highly relevant to the development of mobile wireless networks for lightweight, rapidly deployable forces.

Limiting for Very High Order Discontinuous Galerkin Methods - (Chi-Wang Shu, Brown University) - It is well known that limiters used to reduce or eliminate oscillations near discontinuities can be thought of as a sophisticated artificial viscosity. For finite element methods, such as the discontinuous Galerkin method, it is easier to implement an artificial viscosity than a limiting strategy. Unfortunately, current artificial viscosity implementations fail to completely damp oscillations. By studying the explicit tie between artificial viscosity and limiters, Professor Shu expects to be able design a new artificial viscosity that can maintain its easiness of implementation but achieve the effect of a limiter in gradually reducing the order of accuracy when warranted. Since limiters are well developed for finite volume methods, an alternative approach might be to hybridize a WENO scheme with a discontinuous Galerkin method. The idea would be to use the WENO method when limiting is needed and the discontinuous Galerkin method otherwise. Professor Shu is also exploring this option.

Energy Efficient issues in Wireless Sensors Networks – (Yuanyuan Yang, SUNY-Stony Brook) - A new development in wireless communication networks is expected, which allows for the automatic allocation and re-allocation of message priorities based on message content, length, origin, and other characteristics. This will provide a more informative message stream while providing more noise-free time for the decision making team.

MECHANICAL SCIENCES

Laminar Mixing in Micro- and Meso-Scale Flows: Enhancing Heat and Mass Transfer with Chaotic Advection - The project, recently initiated at Vanderbilt University with Professor Mark Stremler as the Principal Investigator, considers laminar mixing in micro- and meso-scale fluid flows when diffusive transport plays an important role. In particular, this investigation uses analytical and computational tools to determine the ability of chaotic advection analysis, which neglects diffusion, to predict the enhancement and optimization of convective-diffusive transport in laminar flows. Attention is focused on flows in channels with a series of bends, which are of current interest for micro- and meso-scale applications. The results of this work will form the basis for an experimental analysis of heat transfer enhancement in micro and meso-scale flow, and ultimately should produce compact, light-weight, and efficient heat exchangers for tomorrow's high-tech warrior or emergency worker for operation in extreme temperature environments.

High Performance Damping with Carbon Nano-Tube Polymer Composites - Professors Kon-Well Wang and Charles Bakis, Pennsylvania State University are investigating high performance damping with carbon nano-tube polymer composites for the purpose of developing improved structural damping treatments. Their goal is to synthesize novel polymeric damping composite materials by distributing carbon nano-tubes throughout the host polymer. Their research will provide guidelines to configure structural damping treatments using the new carbon nano-tube polymeric composites for the purpose of enhancing the energy dissipation ability of polymeric damping for structural systems. To achieve their goals they are devising controlled processes and methods to synthesize carbon nano-tube based damping polymeric composites with different design parameters. They must then develop (1) constitutive models through the integration of molecular dynamics and micro-mechanics to predict the qualitative and quantitative behavior of the new damping composite and (2) experimental methods to characterize the composite damping performance and validate the analytical predictions. Once these are realized, they will devise system level structural damping models based on the new constitutive models that will permit them to examine the damping ability of the new composite elements on benchmark structural testbeds at the system level. Their research effort has a direct relevance to Army rotorcraft, specifically in the design of rotor blade systems and electronics enclosures. An advanced damping system has a direct impact on system weight, and weight reduction is always a primary mission objective. Army rotorcraft is highly dependent on the quality, life expectancy, and weight of elastomeric materials used in lead/lag dampers. Nano-technology could have a

significant impact on the level of damping obtained in the lead/lag mode, which is generally beneficial to rotorcraft. A typical elastomeric damper weighs about 20 lbs, so a 10% reduction in damper weight would translate into a 10 lbs weight reduction in a five bladed rotor system. It is estimated that each pound of weight savings is currently valued at $1M.

High Strain Rate Fracture of Heterogeneous Materials with Micro and Nano Fillers - This project being implemented at Auburn University under the direction of Professor Hareesh Tippur intends to gain insight into the high-strain rate fracture behavior of light-weight polymeric heterogeneous materials with micro- and/or nano- fillers. The primary task of the research is to investigate the role of filler particle size, shape and filler-matrix adhesion on the effective fracture toughness of the materials under impact loading conditions. Measurements and modeling across spatial dimensions are to be undertaken for bridging scale issues on the fracture behavior. The research will also address related aspects of (a) dynamic crack growth along microstructurally dissimilar interfaces in bimaterials with elastic homogeneity, (b) role of microstructural gradation in the presence of macroscopic homogeneity and, (c) particle size contamination/bimodality effects on dynamic fracture of particulate composites. This research will also address the optimum particle size and particle-matrix adhesion strength for best fracture performance. The anticipated outcome of the research will likely have implications beyond the immediate goals. It is apparent that many military systems require heterogeneous material systems in order to perform optimally. Examination of the fracture behavior of light-weight polymeric heterogeneous materials with micro- and/or nano- fillers under high strain rates will have implications in many military systems that are exposed to impact or blast loading. Since the materials are lightweight they could be good candidates for protective systems. The fundamental understanding gained from this work has the potential to benefit many future Army systems including vehicles, rotorcraft, and structures.

Development of New Electronic Control Strategies Based on a Generic Model for Heavy Duty Diesel Engines – As part of a larger effort to study the application of advanced engine control systems to high power diesel engines, being conducted at Wayne State University by Professor Naeim Henenin, a user friendly platform will be developed for designing and assessing new control strategies that optimize the fuel economy and maximize the power density of advanced commercial diesel engines while satisfying the military requirement of low smoke visibility in the field. The strategy would enable the engine, developed to run on commercial DF-2, to run on military-grade JP-8 fuel.

The engine cycle simulation is for a detailed multi-zone model for direct injection (DI) diesel engines. The model covers the entire engine cycle and accounts for the gas exchange system, in-cylinder processes, engine-out emissions, and engine dynamics. The formulation of the gas exchange system captures the filling and emptying of the intake and exhaust manifolds. The thermodynamics portion of the model will be coupled with the engine dynamics submodel through the overall cylinder pressure and crankshaft angular velocity. The model will account for the rigid body motion of the crankshaft/connecting-rod/piston mechanism. The engine cycle simulation model will be

validated by comparing its results to those obtained experimentally. Furthermore, the engine cycle simulation models will be used to develop control strategies for reducing EGR and determining the appropriate injection timing. These strategies will be validated through experimental results.

PHYSICS

Advanced Quantum Cascade Laser Design and Characterization - Since the invention of the quantum cascade laser (QCL) at Bell Laboratories in 1994, the engineering and optimization of the solid-state device structures has continued. The QCL structure is a series of semiconductor heterostructure superlattices and engineered quantum well active regions designed such that once electrons in the upper state decay radioactively into the lower state, they cascade into the upper state of the next stage in the laser. The quality of emitted light and the efficiency of QCLs are determined by the electron dynamics within the structure and the condition of the numerous interfaces involved in the device structure. The ARO Condensed Matter Physics program has stimulated collaborations among scientists at Harvard University, the University of Michigan, Texas A&M University and the Army Research Laboratory at Adelphi (ARL) to study both the electron dynamics and interface quality in QCLs. Quantum cascade lasers and test structures are provided by scientists at Harvard University and ARL. The electron dynamics is being studied at the University of Michigan using pump-probe techniques with a mid-infrared wavelength pump pulse and up-conversion of the QCL emission. Interface quality is being studied at the University of Texas A&M using world-class cross-section scanning tunneling microscopy (X-STM). This technique provides a direct measurement of cross-incorporation and segregation of atomic species across interfaces – effects that modify the cleanliness of the electronic structure of the superlattices and quantum wells, directly affecting QCL operation. These efforts to understand the physical origins of the device characteristics and quality will lead to advances in the spectral quality and efficiency of these lasers.

Atom Optic Devices for Navigation - There has been a growing understanding and improvement in the design of atom chips. Just recently it was demonstrated that a Bose Einstein condensate could be coherently slit. Since there is not yet shot-to-shot consistency, this is not yet a viable beamsplitter. Within the next year, however, it is expected that a coherent beamsplitter will be demonstrated. Specifically, it is expected that there will be observation of phase-dependent signals in a Mach-Zehnder or "direct fringe readout" interferometer. This will also enable the measurement of the coherence time of the split condensate. Measurements will consist of coherence vs. distance between interferometer arms, and identification of mechanisms responsible for coherence time limit. It is also expected that a Cs BEC on a chip with tunable interactions will be achieved.

To demonstrate the capability for an INS at the DARPA specified sensitivity for navigation applications, it is expected that in the next year there will be a demonstration and test of atom-chip-based high-accuracy atom interference sensors. The required

systems engineering and sensor trade studies will be performed at a detail level sufficient to determine global system architecture.

In free-space interferometer designs, which compete with the atom-chip approach, it is expected that there will be a demonstration of a prototype accelerometer, gyroscope, and differential accelerometer sensor. These sensors will be tested against the sensor performance criteria determined by the systems engineering tasks. Specifically, platform mechanization and the associated sensor requirements will be identified. The overall system architecture will be established. Finally, system navigation performance will be modeled to verify that the required performance specification can be met.

Exploiting Quantum Control - It is now understand how a quasibound molecular state, which is in Feshbach resonance with an incoming atom wave, and is coupled to a nondecaying bound state by an electromagnetic field, will exhibit a kind of quantum interference which can be used to control collision dynamics. One expects numerous applications to follow from this kind of quantum control. Already demonstrated has been Raman self-focusing and defocusing on the one hand, and "Bose-nova" explosions on the other. Moreover, this has been used widely now to control molecule formation via photo association. The most exciting application of control through Feshbach resonances this past year has been in the creation of strong-coupling pairs of dilute Fermions in a regime where there is neither binding nor traditional BCS theory. It is expected that quantum control of this and other sorts will be exploited in the coming years to manipulate Fermion superconductivity, to control atomic beam "lithography"/deposition, to control gate operations in quantum computer architectures, and to "up-convert" atoms into molecules in traps or optical lattices. Quantum control is the engineering of the 21st Century. We will be seeing many future accomplishments based on it.

A CW Atom Laser - Even as the new field of atom optics develops equivalents to mirrors, gratings, and beamsplitters, the importance of the laser cannot be overstated. Although matter-wave or atom lasers have been demonstrated, they are still very primitive. The Physics Division has supported from its inception a project whose realization will be a phase- and flux-stable continuous-wave (cw) atom laser. The primary strengths of this source will be its genuine cw operation and the fact that the beam is confined in a guide structure right from its origin. These properties will make the device the ideal source for atom-interferometric devices, including those being developed currently under the PINS program. In fact, when ready the cw atom laser can simply replace the atomic beam sources now being used. The design being pursued is based on a magnetically-guided, near-hydrodynamic stream of evaporatively cooled atoms. The first step will be to demonstrate its integrability with small, magnetic-guide-based atom-interferometric structures such as atomic Fabry-Perot and Mach-Zehnder interferometers. It is expected that a preliminary beam will come soon.

ARO Core Programs

I. PROGRAM OBJECTIVES

The U.S. Army Research Office (ARO) Chemistry Program advances our knowledge and understanding of molecular science to develop future military technology. Chemistry overlaps and interfaces with other disciplines at ARO: with life sciences for chemical and biological defense and for biomimetic molecular structures; with the materials sciences for the creation of new materials by chemical processing, and with the study of these materials at the molecular level; with physics and electronics in cases where chemical change and chemical structure influence electrical and optical properties; with environmental sciences in the detection, identification, and treatment of toxic materials; with engineering in chemical processing, combustion, and power; and with mathematics in the use of new computational methods in molecular structure and dynamics calculations, and models and simulations of chemical processing.

II. PROGRAM EXECUTION

A. General Information

The thrusts under which most of the supported research is organized are elastomers, electrochemistry and advanced energy conversion, oxidation, colloids and organized assemblies, surfaces and catalysis, fast reaction kinetics, and novel molecules. These thrusts support work to advance our understanding of the basic principles underlying improved elastomeric and other materials; compact power sources; chemical reactors for destruction of military waste materials; solutions for decontamination of chemical/ biological weapon agents; catalytic oxidation or hydrolysis of chemical/biological weapon agents; ignition, detonation, and sensitivity of energetic materials; and new molecules for Army applications. We also pursue research relevant to chemical sensors and environmental cleanup. We coordinate topics of interest with the Office of Naval Research and the Air Force Office of Scientific Research under Project Reliance.

B. Thrusts and Trends/Workpackages

The new grants, contracts, and other activities beginning this year were distributed into the following chemistry work packages:

- *Elastomers for Soldier Protection and Army Materiel:* barrier and permselective polymers, toxic chemical resistance, high performance mechanical properties.
- *Electrochemistry and Power Sources:* compact lightweight power for the soldier and other Army platforms.
- *Oxidation:* destruction of toxic materials by strong oxidizers.
- *Organized Media and Organic Chemistry for Threat Agent Decontamination:* effective non-corrosive decontaminants
- *Surfaces and Catalysis:* chemical agent destruction and protection

- *Fast Reaction Kinetics and Energetic Materials:* fundamental combustion processes for high performance and low vulnerability of explosives and propellants.
- *Novel Molecules for Advanced Army Materiel:* polymer engineering, fibers, novel architectures and compositions for superior performance.

As goals are met and new requirements emerge, workpackages may be closed and new ones initiated.

C. Research Investment

The FY01 allotment for the ARO core chemistry (HB57-08) program was $4.2 million. The Army Materiel Command Research, Development and Engineering Centers (RDEC) and the Army Research Laboratory (ARL) provided an additional $3.4 million. Army funding for the Institute for Soldier Nanotechnology was $9.4 million. The Department of Defense Multi-disciplinary University Research Initiative (MURI), Defense University Research Instrumentation Program (DURIP) and DEPSCOR provided $11.4 million. ARO chemists managed $7.3 million for the Defense Advanced Research Projects Agency (DARPA): most of these funds were for Compact Power and Advanced Energy Conversion. The Small Business Innovative Research (SBIR) and the Small Business Technology Transfer (STTR) programs provided $11.2 million. Research and instrumentation supported within the Historically Black Colleges and Universities/ Minority Institutions and Tribal Colleges program totaled $1.2 million. Total investments in chemistry for FY04 were $49.3 million.

D. Workshops and Symposia -

Thermal Management for Micro- and Meso Power Systems, May 2004: Industry, university, and government experts met for two days to discuss the challenges and research issues associated with thermal management of soldier-portable power sources. Approaches discussed included new and/or innovative use of materials, novel means for thermal integration, and modeling and diagnostics for small-scale devices. Research recommendations are presented in workshop report.

Plasma/Propellant Interactions, October 2003: Army and University experts met for two days to discuss our current understanding, new experimental data, and the state of current models. We made recommendations which were published in a workshop report for the most promising future experiments.

International Workshop on Branched Polymers for Performance, May 2004: This American Chemical Society Workshop brought international experts on branched polymers together with Army scientists to discuss the most recent advances in polymer science and engineering as they relate to branched polymers.

Advanced Air Purification Technologies for CBRN Protection Unit Processes and Systems, October 15-16, 2003: DOD, industry, and university experts met for two days

to discuss the latest innovations and technologies for collective protection. The workshop focused on the need to consider the entire collective protection system when developing new air purification technologies.

Self-Decontaminating Materials and Multifunctional Coatings Workshop, October 28-29, 2003: Government, industry, and university experts gathered for two days to discuss the development of reactive coatings for the neutralization of chemical and biological warfare agents. The workshop highlighted the ongoing Chemical Sciences MURI center at the University of Pittsburg. From this workshop, DARPA has developed the ongoing Self Decontaminating Surfaces program.

Biological Agent Detection and Identification Symposium, March 1-3, 2004: The symposium was a part of the Joint Service Point Detection Conference and focused on the latest advanced technology and basic research for point detection of biological organisms.

DECON 2004 Conference, May 17-20, 2004: This international decontamination conference had over 400 participants from industry, academia, and government programs. The conference focused on all aspects of decontamination including operations through basic research.

III. SPECIAL PROGRAMS

A. Multidisciplinary University Research Initiative (MURI) Program
Bio-Directed Hierarchical Assembly of Multifunctional Materials – University of Massachusetts, Amherst: This new MURI program will explore novel, multifunctional materials by combining interesting biological materials with polymer chemistry. The investigators will explore proteins and viruses and will use self assembly to generate materials with novel architectures and structures. Biological assemblies will be covalently linked to copolymers to generate materials with permanent order and structure.

B. The Institute for Soldier Nanotechnology (ISN), Massachusetts Institute of Technology (MIT). ISN carries out fundamental research relevant to the soldier. The program is unique in that it has founding industry partners that are permanent members and a mechanism for additional industry partners to join and leave the Institute, depending on needs and activities. The industry partners are positioned to receive promising technical results and work to bring new products and capabilities to the soldier. Research in the ISN falls into two broad categories: (1) physical protection and processes and (2) chemical and biological protection and processes. Research in these areas is carried out by seven teams that focus on experimentation, and modeling and simulation on energy absorbing materials, mechanically active materials, sensing and detoxification, biomaterials, and processing.

C. DOD Experimental Program to Stimulate Competitive Research (DEPSC0R)
"First Principal Predictions of the Crystal Structure of Energetic Materials" is a new grant to University of Delaware. This project grew from an ARO 2003 workshop, "Computational Tools for Condensed Phase Properties" and supports Army research on new energetic materials design.

D. Small Business Innovative Research (SBIR) New Starts:

Safe Packaging of Ammonia for Compact Hydrogen Sources: Phase II start with MesoSystems Technologies, Inc. OBJECTIVE**:** Develop a lightweight, low-cost ammonia adsorbent that when used in a compact storage and delivery system releases ammonia at near-ambient conditions at a sustained maximum rate of 0.12 g/min. Thermal decomposition of 0.12 g/min of ammonia produces sufficient hydrogen to produce 20 W (electric) from a hydrogen/air fuel cell.

Small Scale Fuel Cells for Ground Personnel: Phase II start with Mesoscopic Devices. OBJECTIVE: Develop innovative low-pressure air compressors that are suitable for pressurizing small fuel cell systems. Phase II start with Protonex Technology Corp. OBJECTIVE: Develop low-cost portable PEM fuel cell stacks.

Mixed-Feed Direct Methanol Fuel Cell: Phase II starts with Mesoscopic Devices and Gibbard Research and Development Corp. OBJECTIVE: Develop a compact 20-W direct methanol fuel cell system that uses mixed-reactant feed of air + methanol (aqueous) to one or both electrodes of a polymer electrolyte membrane fuel cell. The system should include all balance-of-plant auxiliaries, such as fluid moving equipment, heat exchangers, and storage vessels. The power system should be compact (> 1 kW/L and >1 kW/kg), energy dense (> 1kWh/kg), and supply 1 kWh of energy.

Catalytic Coatings for Chemical Protection – This effort will develop new coatings to neutralize chemical warfare agents and other hazardous chemicals. The new phase I effort at TDA will screen new catalysts and study the fundamental kinetics and reaction products of the catalysts in a coatings system.

Colorimetric Sensors for End-of-Service-Life Indicators for Mask Filters – K&M Environmental and Chemmotif are developing indicators for incorporation into mask filters which will signal when the filter is reaching its capacity and breakthrough of a hazardous chemical is imminent.

E. Small Business Technology Transfer (STTR) New Starts

Membraneless Microchannel Fuel Cells: Phase II start with INI Power. OBJECTIVE: Develop a compact 10-W fuel cell system that (1) uses a microchannel, membraneless fuel cell, and (2) includes all balance of plant auxiliaries, such as fluid moving equipment, heat exchangers, and fuel/oxidizer storage vessels. The fuel cell power system should be compact (> 1 kW/L and >1 kW/kg), energy dense (> 1kWh/kg), and supply 1 kWh of energy.

Metal-Organic Framework Adsorbents for Fuel Cell Relevant Small Molecules:
Phase I contracts awarded to Physical Sciences Inc., Synkera Technologies Inc., T/J Technologies, Inc, and Triton Systems, Inc. OBJECTIVE**:** Design and develop robust metal-organic framework (MOF) materials that selectively remove small molecule contaminant(s) produced by a fuel cell's fuel processing system. Package MOF material as a component in a compact fuel processing system sufficient to support a polymer electrolyte membrane 20-W fuel cell for 72 hours. Target minimum energy density for the fuel processing system, including fuel, is 1.5 kWh/kg or 90 g of hydrogen per kg of system weight.

Improved Kit for Chemical Agent Detection – This new phase II effort at Materials Technology Corporation will improve the response and reduce false signals when compared to existing systems like M8 and M9 papers. The paper kits to be developed will be no power systems with a strong resistance to interferents.

Viability Assay for Monitoring Decontamination of Pathogenic Bacteria – This new phase II effort at Luna Innovations will be developing a protocol and the technology to verify the removal of biological organisms during a decontamination procedure.

Fast Laser Pulse Shaping for Molecular Control and CB Detection – Two phase I projects began (Biophotonics Solutions, Proteus) based on research from ARO core grants over the past decade and a nearly completed MURI (Optimal Quantum Dynamic Discrimination of Chemical Agents). This project will develop hardware to enable other labs to perform optimal laser control of molecular motion.

IV. SCIENTIFIC ACCOMPLISHMENTS

Ammonia as an Energy Source
Professor Richard Masel, UIUC

Under the MURI program on Microchemical Systems, this group has successfully modeled cracking of ammonia in small reactors of various physical designs. The model can properly treat the low Reynolds regime in these reactors and accurately predict the better performance of microchannel reactors vs. 'post' reactors.

Macromolecular Architecture for Performance
Professor Tim Long, Virginia Tech

Well-defined branched polyolefins with the potential for unsurpassed performance at low material cost are being synthesized from inexpensive monomers using living olefin polymerization catalysts and a macromonomer copolymerization approach. A macromonomer copolymerization approach is being used with the goal of discovering new branched polyolefins that can be used as additives to improve the processability of commercial polyethylene. The effects of polymer architecture on polymer physical properties are being studied in collaboration with ARL-WMRD.

Conveyor Belt Transport, Rotation and Separation of Arbitrary Collections of Nanoparticles
Professor Robert Carpick, University of Wisconsin-Madison

The objective of this research is to demonstrate versatile linear motion, orientation alignment, and mass and species separation of organic and inorganic nanoparticles through the development of a thin film nano-conveyor belt. Nanoparticles are deposited onto the substrates, and mechanical actuation through piezoelectrically-induced inertial motion is used to manipulate the nanoparticles. During the first year, the investigators have been able to successfully move individual particles in controlled directions, and they have selectively moved particles based on their size. The goal of this research is to fabricate prototype nano-conveyor belts and demonstrate the manipulation of a wide variety of nanoparticles.

Developing Combination Sorbent and Reactive Chemistries for Use in Sensitive Equipment Decontamination
Professor Michel R. Gagne, University of North Carolina at Chapel Hill

Professor Gagne's group has developed a family of designer sorbents for sensitive equipment decontamination. These materials sorb contaminants (agents, simulants, etc) from the fluorinated solvents used to clean sensitive equipment (microelectronics, optics, coatings, etc.), which are otherwise incompatible with organic and aqueous cleaning solutions. The properties of fluorinated solvents that make them compatible with sensitive equipment simultaneously make them difficult to clean. Professor Gagné's sorbents are designed to work most efficiently in fluorinated solvents and provide a solution to the problem of waste stream cleanup. Gagné is currently working on enhancing the uptake efficiency of the materials by the incorporation of functional groups that chemically react with the agents and simulants. This provides a large driving force for agent uptake and simultaneously provides a method for including a diverse range of reactive groups for a broadened spectrum of reactivity (for e.g. VX and mustard). Current efforts are aimed at developing new reactive groups for sorbent incorporation for optimal fluorinated solvent cleaning.

Laser Control of Molecular Motion
Professor H. Rabitz, Princeton University

Support from DURIP enabled design and assembly of a fully functional closed loop laser control system including pulse shapers, sample cells, detectors, and associated high speed electronics. This unique system has been tested using laser control to manipulate the fluorescence signals from dyes. Now this equipment will support the MURI project on Optimal Quantum Discrimination of Chem/Bio Weapon Agents in which laser control optimizes the detection signal from threat agents. The following figure shows the complex path required for shaping the fast laser pulses and some of the optical components.
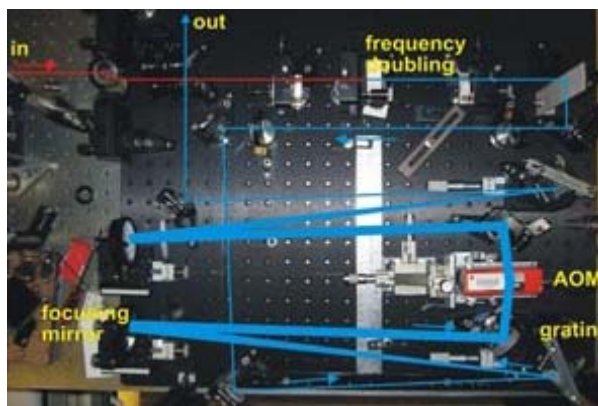
New Diagnostics for Propellant Combustion
Professor Terrrill Cool, Cornell University

Having pioneered the use of flame sampling photo ionization mass spectrometry,
Professor Cool used it for measurements of absolute species mole fraction and flame
temperatures for NO2/O2/H2/Ar and O2/H2/Ar flames doped with (CHO)2, H2CO and
HCOOH, three common gaseous components of the thermal decomposition of nitrate-
ester propellants. This is the first such data ever measured and will provide reliable input
for Army combustion models.

V. TECHNOLOGY TRANSFER

Compact Power
Phoenix Analysis and Design Technologies

Successful product development has led to the sale of blowers and compressors
developed under an ARO sponsored SBIR project to UTC, GE, Isuzu, Hyundai and other
major auto companies.

Compact Power
Mesoscopic Devices

Successful product development has led to sale of evaluation quantities of small pumps
developed under an ARO sponsored SBIR to various developers of compact power
sources.

MAP MURI
Virginia Institute of Technology

Investigators at Virginia Tech are collaborating with ARL-WMRD and have exchanged
sulfonated poly(styrene)-poly(isobutylene)-poly(styrene) triblock copolymer membranes

for evaluation in actuation applications as part of a study to understand the effects of polymer ionic content, modulus, and water content on transduction properties.

Investigators at Penn State are collaborating with ARL-WMRD to study the morphology and rheology of self-associating hydrophobically-modified methacrylate copolymers and uracil-functionalized polyacrylates and polystyrenes synthesized at Virginia Tech using atom transfer radical polymerization (ATRP) techniques. A graduate student from VA Tech participated in a student intern program at ARL-WMRD for the summer and worked on several Army projects, including studying the self-assembled morphology of block copolymers that are chemically modified modification to template the formation of ultra-high density ordered arrays of nanoscale gold films, and the formation of spherical cavities that are arrays of micrometer-sized water droplets formed during vapor condensation onto a polymer solution surface.

Decontamination Verification Assay
Luna Innovations, Blacksburg, VA.

Supported by the U.S. Army SBIR program, Luna Innovations has developed several rapid, fluorescent viability assays for studying the efficacy of decontaminants against bacterial pathogens without the use of conventional plating methods. The assay formats target general and specific enzyme activities and can be performed in one to two hours. Luna has developed protocols for monitoring the decontamination of bacterial spores from spore-coated surfaces within eight to ten hours. This decontamination verification technology is being evaluated in collaboration with the NSWC-Dahlgren and Battelle.

Army Incinerator Simulator
REI, Inc., Salt Lake City, UT

This Phase II Plus SBIR project provided support to the Army and their contractors for operating chemical weapon incinerators. This support led to substantial savings and REI was awarded an Army 2004 SBIR Quality Award at the Pentagon. REI now has contracts with other Army projects and with the EPA in support of Homeland Security. The figure shows a simulation of temperatures and droplet trajectories for VX in the Liquid Incinerator.
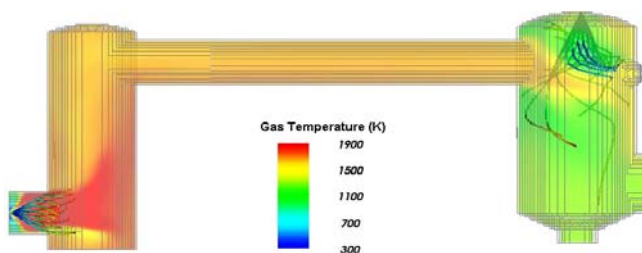
Energetic Molecule Design MURI: Crystal Packing
University of Maryland

Computational chemistry codes developed by University of Maryland scientists are being used in their collaboration with the Army to predict crystal structures and densities of energetic materials. This work is part of the Army program on energetic material design.

VI. DIVISION STAFF

Professor Peter Fedkiw
(North Carolina State University) Intergovernmental Personnel Act Employee supporting Advanced Energy Conversion

Dr. Douglas J. Kiserow,
Polymer Science and Engineering: Synthesis, Self-Assembly, Architecture; Detection and Identification; Program Manager for Institute for Soldier Nanotechnology; Director (Acting), Physical Sciences Directorate

Dr. Stephen J. Lee
Organic Chemistry: Organized Assemblies, Surface Chemistry and Catalysis

Dr. Richard J. Paur
Electrochemistry and Advanced Energy Conversion: Mobile Power Sources, Electrochemical Synthesis

Dr. Robert W. Shaw, Associate Director
Physical Chemistry: Fast Reaction Kinetics, Chemical Reactors

Brian Moyer
Administrative Support Assistance

COMPUTING AND INFORMATION SCIENCES

I. PROGRAM OBJECTIVES

The principal objective of the Computing and Information Sciences (CIS) program is to provide increased performance and capability for processing and communicating signals, data, and information to enhance the warfighters' decision making, situation awareness, command and control, and weapons systems performance. This program identifies and addresses the Army's critical basic research problems in CIS where progress has been inhibited by a lack of novel concepts or fundamental knowledge. CIS is pervasive in nearly all Army systems especially Command, Control, Communications, Computing, Intelligence, Surveillance, and Reconnaissance (C4ISR) systems. Research in this program has application to a wide variety of developmental efforts and contributes to the solution of technology-related problems throughout the Army's Future Force operational goals. The program consists of five subareas of research managed by individual program managers.

Information Processing, Fusion and Circuits - includes computer vision for target acquisition and robotic vehicles; information, data, and sensor fusion; digital signal processing; integrated circuits for information processing and wireless communications; and low energy dissipation information processing and circuits.

Communications and Networks - focuses on research for the implementation of multimedia, adaptive, and distributed mobile wireless communications to provide networks for communications-on-the-move on the battlefield of the future.

Software and Knowledge-Based Systems - The foci of this program include a focus on the current lack of technology supporting a principled system/software engineering discipline. Included also, is a concern for addressing the needs for improving technologies supporting advanced data/information/knowledge acquisition, representation, and data/information processing/storage; natural language understanding, intelligent agents, autonomous systems, information fusion, and man-machine interfaces.

Systems and Controls - is concerned with modeling, analysis, design, and robust control of complex real-time dynamic systems including distributed and embedded, networked autonomous and semi-autonomous, non-linear, embedded and hybrid, smart structures, and decentralized systems. The program also involves innovative research on emerging areas such as net-centric control, quantum control and computation, and the interaction of control with biology and medicine.

Information Assurance - addresses the delivery of authentic, accurate, secure, reliable, and timely information, regardless of threat conditions, over heterogeneous networks consisting of both tactical (mobile, wireless) and fixed (wired) communications infrastructures.
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COMPUTING AND INFORMATION SCIENCES

II. RESEARCH PROGRAM

A. General Information

The role of the Army and other U.S. forces has been changing in the last decade or two from one of massing heavy forces against a numerically superior enemy force to one of responding to multiple outbreaks of conflict or to address problems of human suffering. The terrorist attacks of September 11, 2001 on the World Trade Center have defined a significant mission to respond to the war on terrorism.

The Army has also determined from its experience in the Gulf War, Afghanistan, and Iraq that it needs a force that can be deployed rapidly to any conflict area in the world and has begun transformation to a lighter, more mobile force to meet the challenges of nonlinear warfare in a multi-polar world with a wide range of potential enemy forces, from highly organized forces to regional threats, as well as, terrorists. The delay incurred in deploying a heavy force with 70 ton tanks is no longer acceptable nor is the logistics tail needed to support it. The Army has embarked on a transformation to a lighter more rapidly deployable and supportable force.

The operational concept of the Future Force includes smaller units with higher mobility and weapons of greater precision and lethality. Since forces will not be highly massed and vehicles will have less physical protection, the key to providing survivability of this force is to make real-time information on the friendly and enemy situations available continuously so that decisions can be made and actions taken within the decision cycle of the enemy. Information processing on-the-move is critical to the success of operations of this constantly mobile force. Since the force is mobile, mobile wireless communications networks are required that are adaptive and can operate on-the-move without any fixed (non-mobile) infrastructure. There will be numerous unmanned robotic and teleoperated aerial and ground vehicles serving as sensors, communications relays, and weapon system platforms. The number of information sources on the battlefield is growing rapidly. Computing and information processing research has to provide the technology to process this growing information in real-time and to insure that soldiers and commanders are not overburdened with data to a degree that adversely affects their performance and the outcomes of battles.

The transformation of the Army from a Legacy Force to the Future Force will require investment in science and technology, especially computing and information science. The research topics described here are those needed to provide the Future Force the information processing, communications, and control systems needed to achieve the vision of future Army operations.

The computing and information systems capabilities required to support the Future Force center around techniques to gather, disseminate, and act upon information about the enemy's location, movement, and intention and to maintain friendly and enemy situation awareness. Information from many different information sources have to be fused to produce a total picture of the battlefield. This composite of information must be

communicated quickly and reliably to both men and machines. Methods to aid the Commander in using this information effectively must be developed. Decisions generated by the Commander must result in unified action plans communicated quickly by electronic systems. Computing and information systems also play a key role in providing an increased range and kill probability of weapon systems. For this reason, CIS is a key technology, underpinning the Future Force.

B. Thrusts and Trends/Workpackages

INFORMATION PROCESSING, FUSION AND CIRCUITS

The increased capability of electronic systems and a proliferation of sensors are generating rapidly increasing quantities of data and information to the point that systems operators and commanders are becoming saturated with information. The performance of sensor systems can be greatly improved by combining information obtained from more than one source or from sequential frames of information from the same source. For these reasons, research is performed to investigate methods for fusing information obtained from multiple sources, sensors, or frames. This research will address the identification of the basic properties and features in information and sensor signals to determine the information important for Automatic and Aided Target Recognition (A/AiTR) and fusion. Information metrics, decision theory under uncertainty, representation of information from sources of differing modalities, and methods for combining information and representing fused information are considered.

A/AiTR is a challenging problem because the environment is not constrained or controllable and changes continuously. The scene background is cluttered, the objects are typically far away (at extended range) with few pixels on target, and the view may be obscured or blurred. Novel sensing modalities, both imaging and non-imaging, need to be investigated. In addition, arrays of sensors (possibly consisting of multiple modalities) may be employed. Implicit in the operational requirements of all these sensors is the desire for minimization of energy consumption. In general, the focus of this program is the pursuit of theories, algorithms, models, and metrics, which will result in robust, high performance automatic and aided target acquisition systems and in the development of methods to measure and validate the performance of such systems.

Improvements are needed in the performance (especially in the false alarm rate) of current A/AiTR systems. The availability and fusion of large bodies of information from diverse sources may allow unique characterization of objects, particularly when the sensors provide nearly orthogonal information. Examples include acoustic and infrared (IR) sensors. Forward Looking IR (FLIR) and visible provide information about both the thermal properties and the reflectivity of target surfaces. Radar and Lidar can provide range and 3-D information of the target. Imaging sensors may include hyperspectral, multispectral, and polarimetric imaging.

Important aspects of fusion research include identification of metrics, features, and algorithms, which result in complementary integration of information from multiple

source modalities which may include human intelligence. Fusion seeks to improve the performance of decision-making processes under uncertainty and includes the study of information theoretic or epistemological issues of data to identify a common temporal and spatial framework (4-D) and to resolve ambiguities and contradictions.

A/AiTR is of paramount importance to the success of the Future Force. This program must look forward and consider the impact of the characteristics of future warfare on technological needs. For example, the resolution of sensors has increased but the aperture for missile sensors has not since the diameter of the missile has not changed. Increased mobility and dispersion of forces in smaller units, has created the need for sensors to perform large area search. The use of smaller, lighter vehicles operating at much faster speeds and active camouflage makes detection, classification, recognition, and tracking of targets more difficult. Increased use of satellite sensors and increased numbers of sensor modalities increases the quantity and complexity of data. Increased use of indirect fire; autonomous, precision guided munitions; and remotely-piloted and autonomous vehicles also increases the complexity of information processing.

Efficient digital signal processing algorithms and architectures performing communications, intelligence, surveillance, target acquisition, and detection functions that are suited to low power integrated circuit implementation are required. Of particular interest is the use of concurrency to obtain high throughput and faster computation. Image modeling; target detection, classification, and identification; and moving target tracking are being studied.

Soldier's radios and other electronic equipment are powered by batteries which must be carried by the soldier as part of his personal load. This program investigates the design of RF and processing circuits not only to minimize the weight of electronics and batteries carried by the soldier but also to minimize the energy consumption rate in order to extend mission times. Research focuses on RF circuits for radios emphasizing circuit design to enable a transceiver on a chip for very small, highly energy efficient transceivers and on efficient architectures, algorithms, and circuits for information processing.

COMMUNICATIONS AND NETWORKS

Research is concerned with the application of communications theory, wireless networking, signal processing, and mathematics to the fast, accurate, reliable, and efficient transmission of information for the digital battlefield.

Because of their low probability of intercept, anti-jam, and multiple access characteristics, spread spectrum techniques are important to Army communications, intelligence, surveillance, and target acquisition systems. Methods for design and performance analysis of spread spectrum systems are studied. Research is also sponsored in other innovative approaches to communication such as ultra-wideband communications that offer low probability of intercept and high immunity to jamming and interference. The vulnerability of spread spectrum systems to jamming and interference and the use of adaptive electronic counter countermeasures (ECCM)

techniques to improve network performance in the presence of jamming and interference are investigated.

The concepts of light, agile forces and the digital battlefield require a seamless, ubiquitous, survivable and highly mobile wireless communication system with a highly dynamic network topology. Information communicated ranges from voice to video and includes burst file transfers for radios in vehicles and aircraft and carried by soldiers on foot. The channels are noisy and fade rapidly due to jamming, mobility, multipath, and multi-user interference. To provide the necessary capability, research is supported in spread spectrum, mobile ad hoc, packet radio networks in the areas of multimedia network architectures, protocol engineering, distributed routing and congestion control, and heterogeneous network integration. Research is also supported in adaptive source and channel coding, adaptive antennas for spatial diversity and spectrum reuse, adaptive routing to avoid failed nodes, and power control. Data compression research is needed to enable transmission of broadband signals over the limited bandwidth and high bit error rate of wireless communication channels.

SOFTWARE AND KNOWLEDGE-BASED SYSTEMS (SKBS)

Based on the current lack of technology to adequately support a principled system/software engineering discipline, this program specifically supports research that addresses the perceived engineering technology needs for a future system/software engineering capability. Motivation for this emphasis derives, partly, from a relatively recent report that cited the need for new and revolutionary approaches to achieve the theoretical advances with potential to lead to acceptable technological capabilities supportive of system design, development, and sustainment (evolution). Hence, the SKBS program, with the help of the international academic community, is attempting to develop an adequate vision for future system/software engineering capabilities. With this vision and an adequate assessment of the present state-of-technology, the open-research issues can be better articulated. These open-research issues can then be used to help define a critical-path for future research that has a potentially high-payoff return-on-investment; this strategy also provides a strong basis for judging the relative and potential merits of any given research. The evolving SKBS "vision" for enabling a principled system/software engineering discipline involves an "end-to-end" (requirements to fielded system with accurate documentation), machine-based, integrated/coupled, and interactive suite of tools and user interfaces to accomplish the principled design, implementation, and on-going evolution of software-based systems.

A second focus, often considered in isolation, is that of data/information/knowledge-acquisition, representation and processing/storage. However, there are strong connections, of this information-based concern, to the general software/system engineering research cited above. The need to design a data/information-oriented suite of software is an engineering challenge in itself, and the general software/system engineering problem requires advances in dealing with representation, storage, and retrieval of system documentation.

COMPUTING AND INFORMATION SCIENCES

This multi-disciplinary data/information research area tends to involve the traditional domains of several disciplines including those of databases, artificial intelligence, mathematics, etc. The scope of the fundamental problems, which this area addresses, includes the processing of massive amounts of heterogeneous, multi-modal/media, temporal/dynamic, and distributed data. Here, data is defined as archived, and/or on-line images/signals, etc. The applications related to the SKBS "information concerns" often involve decision support, and/or the active monitoring of environments/networks/systems (performance or situation assessment). These data/information-intensive applications also often require addressing: uncertainty/incompleteness; interactive/autonomous system behaviors; machine-reasoning/learning; monitoring of adaptive/dynamic networks, and adaptive system- response behaviors. A central issue of the "information concern" is that of information-fusion; specifically, this requires the need to extract and/or synthesize rational interpretations, from often "ambiguous" sensor-data, dealing with uncertain/incomplete heterogeneous data-resources, the use/integration of domain/application knowledge , consideration of the environmental/application-context, and mathematical decision-support constructs.

The several other areas of significant importance to the SKBS program include Natural Language Understanding/Formalization, Intelligent Agents, Autonomous Systems, and Man-Machine Interfaces. Anticipated advances in these areas are expected to contribute to achieving the overall objectives of the SKBS program. Selected topics in these areas, particularly those of a multi-disciplinary nature will be considered for funding. Crosscutting areas of Army interest within the SKBS program include the need for advances in system user/operator interfaces, in addition to those areas cited above.

Succinctly, the central SKBS program emphasis is in the areas of new/revolutionary methods and approaches for (1) software/system prototyping, development, documentation, and, evolution, (2) formal methods for software engineering, and (3) theoretical advances in support of the development of technologies for knowledge-based and/or information-intensive systems implementations with improved capabilities.

In addition to the above, there are presently two research initiatives funded thru the SKBS program. They are the High-Confidence Embedded Systems (HCES) Initiative, and Virtual Parts Engineering Research Initiative (VPERI). The HCES initiative addresses the concerns for system engineering technology needs for support software-enabled embedded systems. The VPERI is attempting to improve current CAD/CAM capabilities; in particular it is addressing the critical need for compatible "CAD tools", the coupling of CAD/CAM, the need for enhanced system design-data, and the standardization of data packages. Within the VPERI effort there is a strong focus on addressing the need for legacy system maintenance, and the need to dramatically improve engineering/manufacturing capabilities to provide system- parts.

As indicated above the SKBS program supports research in a number of potentially high-return –on-investment areas including:

- Integrated Computer-aided/Collaborative Requirements Elicitation, Refinement, and Validation.
- Interactive Computer- based Approaches for Machine-Representations of Specifications from Machine Validated Requirements.
- Methodologies/Tool-Sets for Executable Rapid Prototype Construction.
- Automation of Production of System Requirements and Design Documentation.
- Software/System Engineering Tools, Tool-Sets, and the Integration of Engineering Environments.
- Software/system Design, Analysis, and Validation Methodologies.
- System Re-engineering Methodologies.
- Support for Distributed/Collaborative System Design/Evolution.
- Concurrent (Hardware System/Software) and Embedded System Methodologies.
- Software Generation, Evolution, and Re-use.
- Methodologies for Semi-automated Conversion of the "Programming-Language's of Legacy/Domain-specific Software to the "Analysis/Design-Languages" of Engineering-platforms.
- General-Inference Engines/Methodologies.
- Information-Fusion.
- Issues of Dealing with Heterogeneous, Distributed, Multi-Modal/Media, Temporal/ Dynamic Information.
- Human-Computer Interfaces.
- Intelligent Agents and Autonomous Systems.

SYSTEMS AND CONTROL

The Systems and Control Program is concerned with modeling, analysis, design and robust control of complex dynamic systems, especially as they relate to the Army's mission. In addition to traditional areas, the program emphasizes research addressing the Army's move to more agile, readily deployable lightweight forces. In particular, control designs for distributed and embedded, networked autonomous and semi-autonomous systems, embedded and hybrid systems are of interest. The program also involves innovative research on emerging areas such as modeling and control for battlefield management, intelligent missile guidance and navigation, smart structures, quantum control and computation, and interaction of control with biology and medicine.

Networked Autonomous, Semi-Autonomous Systems and Robotics - The anticipated dynamics of the future battlespace will require a greatly increased level of automation to enable the necessary mobility, sensor coverage, information flow, and responsiveness from operation centers and platforms to support the military goals of information superiority, dominant maneuver, and precision engagement. Intelligent collaborative networks of software and physical agents will allow the Army to satisfy this increased tempo within the constraints of reduced manpower and casualties.

The Autonomous and Semi-Autonomous System Thrust Area captures the potential synergy in the advancement of collaborative, intelligent agents. These agents (software and physical) must perform in hostile, uncertain, and dynamic environments. The collaborative, dynamic behavior of these agents must supplement the activities of their human partners. Human/computer interaction with these agents must be highly efficient and minimally intrusive. The agents' complex adaptive behaviors and control must be visualized in a battlespace context. Global/local information fusion must be a part of this representation. Research areas range from the interplay of autonomy and interoperability, to dependability and reliability, and to abstraction and dynamic resource management, to name a few.

Warfighters seek improvement in the design and functionality of current operation centers. Improvements are especially sought for the lack of mobility, inefficiency, and the high complexity of these centers. The extensive hardware, software, and manpower resources needed to operate a center severely limits the mobility for the future battlefield. A greatly increased level of system automation is needed to both significantly lower the human resources required and to improve information flow. Much of this automation can be achieved by collaborative networks of software and physical agents. Physical agents will be ubiquitous in the future battlefield to significantly lower the risks to our warfighters. These physical agents will complement future manned systems and therefore they must be able to collaborate not only amongst themselves, but also with their manned partners. Their roles will range from scout missions performing reconnaissance, surveillance, target acquisition, and urban rescue missions.

Specific problem areas include, but are not limited to, the following:

- Integrated agent-based decision and control architectures, where the agents can include software modules, human users, and physical systems.
- Dynamic resource management, so that the multiple competing demands on scarce platform resources—computing, communications, power—can be automatically balanced in unpredictable, nonstationary environments.
- Fault-tolerant reliable operation, including dynamic-model-based diagnostics, prognostics, and equipment and system health management.
- Abstraction architectures for semi-autonomous systems that suggest a roadmap for increasingly autonomous operation of complex military systems.
- Multi-UAV and -UGV coordination, including languages for coordinated control, stability analyses of distributed systems under partial information, and high-level task assignment.

Control of Nonlinear and Complex Systems - Nonlinear dynamical phenomena are known to occur in a wide variety of engineering systems. Phenomena such as bifurcation and chaos can dominate system behavior should the system be forced to function outside its normal range. The system can enter a limit cycle motion, behave chaotically, or undergo complete system failure. There has been significant work on the control of nonlinear phenomena in recent years, including several experimental demonstrations in a variety of areas including electric circuits, lasers, jet engine compressors, and thermal

convection. While there are many challenges, highly complex nonlinear systems represent real opportunities for developing fundamentally new approaches for exploiting dynamical effects such as the so-called "butterfly effect" associated with large sensitivity to initial conditions. Innovative approaches are needed that address practical issues such as uncertainty, disturbance accommodation, and control constraints.

The ARO is interested in seeing the development of new tools for control of nonlinear dynamics that are inspired by and applied to problems of interest to the Army. For instance, the ARO is interested in tools for the analysis, design, operation and control of distributed networks containing many agents that employ distributed sensing and actuation. The modeling, analysis and control of such networks can be considered. Emergent and self-organizing behaviors of such networks can be studied. A challenging problem in this context is achieving a desired emergent behavior through system design and/or through control design. Other applications of interest include stability control and vibration control of vehicles, robotic mechanisms, flow control, control of lasers, control of combustion, and possible implications of nonlinear phenomena for the dynamics and control of mobile wireless networks.

Convergent Control, Communication, and Information Technologies - There is increasing awareness within the technical community of the need to better understand the interplay between control, communications, and information technologies. Specifically, research is needed to effectively guide the development and deployment of networked communicating control systems, distributed sensor webs, control systems with communication bandwidth constraints, and various software enabled control systems.

The supporting foundations for such systems will require the development of new concepts in control as well as new control-specific concepts in communications and information theory. Such conceptual foundations include new techniques for efficient data encoding for controlling complex physical systems (e.g. combustion and fluid systems), probabilistic and randomized decision models for control, new concepts in information theory based on physical complexity rather than probabilistic models of noise, and new concepts in optimal control which account for implementation and operation costs as opposed to classical models which account for the cost of state output and input deviations from ideal values.

Classical optimal control theory has been almost entirely concerned with costs associated with outputs or states deviating from some ideal values (set points, reference trajectories, etc.) together with costs associated with providing control inputs. A distinguishing feature of what has become widely known as intelligent control is the inclusion of computers and communications devices in feedback loops. These introduce additional cost elements associated with information processing and computation that now need to be accounted for explicitly in control system designs.

Control of Hybrid and Embedded Systems - The dynamic behavior of many practical systems is determined by interacting continuous and discrete dynamics that give rise to hybrid dynamical system behavior. This is the case when digital information systems

interact with the continuous physical systems (e.g. when embedded digital processors interact via sensors and actuators with the physical world). Other examples of hybrid systems of interest to the military include: the missile guidance process; UAVs and UGVs; small communication satellites coordinating continuous maneuvering actions via discrete commands; coordination of autonomous or semi-autonomous robotic vehicles; command and control networks; hierarchical organizational structures where discrete decisions affect the continuous behavior of physical systems; and hierarchical intelligent systems.

To understand the dynamic behavior and build useful hybrid systems one needs to combine and build upon knowledge, ideas, and methodologies both from the discrete world of information/computer systems and the continuous world of physical phenomena. Novel methodologies need to be developed and old methodologies need to be adapted and enhanced to deal with the hybrid nature of systems. There are cases when considering separately the discrete and continuous parts of the system, as has been the practice before, may be adequate. However, to build high performance systems, especially when there is tight interaction between the discrete and continuous dynamics, one must consider explicitly the hybrid nature of the system under consideration. In particular, we need to address fundamental issues involving the interface between the continuous and discrete dynamics such as the issue of discrete abstraction; we need to address issues such as stability and robustness in a manner appropriate for hybrid systems. We need to address the problem of optimal control in hybrid systems and more generally, address the issue of synthesis of hybrid control systems. Methodologies should be based on mathematical formulations and must provide enough confidence in the design to reduce the amount of necessary simulations for validation and testing. In the past, system design methodologies were developed primarily in the continuous, and to a lesser extent in the discrete domains. Now the challenge is to design new methodologies and tools to deal effectively and take full advantage of the hybrid character of systems. This is difficult, but the pay-off comes with the ability to build truly high performance systems that interact efficiently and effectively with the real world.

Embedded digital devices linked via a communication network that coordinate their actions towards some common goal are expected to proliferate in both military and commercial applications. Military applications include networks of embedded systems in sensing and weapons platforms, vehicles, soldiers and command and control organizations. When embedded digital processors interact with the physical world, hybrid dynamics play a particularly important role. Networked embedded processors may communicate over unreliable wireless links and therefore the amount of information that may be reliably transmitted should be considered in the design of such systems. We are witnessing a convergence of the communications, computing and control and this is particularly evident in the case of networked embedded systems that interact with the physical world. In the design of such systems one needs to address several issues including dynamics induced by real time issues, e.g. random delays, issues of autonomy and degree of autonomy, hybrid dynamics issues, as well as discrete event and hybrid system supervisory control issues. It is also important to develop software appropriate

for the implementation of algorithms on small experimental platforms as demonstrations and as proof of concept of the methodologies.

Other Topics - Systems and control is inherently an interdisciplinary area. Applications are a key driver for the development of systems and control theory and techniques, and the theory tends to be used in new applications subsequent to its development. Because of the open-ended and rich nature of this subject area, the ARO Program in Systems and Control will be interested in topics other than those listed in the thrust areas above. These include, but are not limited to, approaches to modeling and control of physical processes, and control of quantum systems.

INFORMATION ASSURANCE

Information assurance for the individual soldier and for the systems that the Army must employ in the next few years is of paramount importance to the defense of this nation.

Characteristics and concepts of operation of the Future Combat System (FCS) include lethality, survivability, mobility, agility, and sustainability. The need for authentic, accurate, secure, reliable and timely communication and information permeates these characteristics and concepts and is vital to the success of FCS. The Objective Force must have unprecedented situational awareness (including enemy and friendly awareness) at all times. It follows then, from the Army perspective, that Information Assurance must address the delivery of authentic, accurate, secure, reliable, timely information, regardless of threat conditions, over heterogeneous networks consisting of both tactical (mobile, wireless) and fixed (wired) communications infrastructures.

Unfortunately, the state of information assurance technology relative to Army needs suffers from a number of serious shortfalls that need to be addressed by a vigorous and directed research program. Current techniques/systems detect only known vulnerabilities, do not guard adequately against distributed denial of service attacks, do not perceive indirect attacks, and have high false alarm rates. The current products and technologies do not scale for high-speed data traffic or volume (bursty traffic is a specific problem related to high performance computing). Current intrusion detection systems have no predictive capabilities, are computationally inefficient, have poor reporting mechanisms, and are not compatible with noisy, wireless channels. From a battlefield perspective, current technology is not adaptable to dynamic conditions, does not fare well under severe constraints (bandwidth, energy, processing, intermittent connectivity), and is not developed to withstand electronic warfare threats.

As the Army places more reliance on winning the information war and providing the individual solder with highly automated and sophisticated tools, there must be an increased and improved awareness of the vulnerabilities that these systems of systems possess. Ubiquitous, mobile, wireless, scalable, high-speed, and highly assured information processing systems will be placed in areas of usage never imagined in the past. Attacks on these systems will occur from hostile forces in both time of war and time of peace.

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The ARO program in Information Assurance addresses seven major problem areas:

- Information Assurance for Wireless ad hoc Networks and Sensor Networks - The system needs to process information with integrity, confidentiality, and authenticity protection. In addition, survivability, self-healing, and energy efficiency are highly desired for these systems.
- Assured Scalable Security Mechanisms for High Performance Computation and Networks - Intrusion Detection, Fault Detection, Quality of Service, and Performance Monitoring.
- Information Assurance Metrics in the Tactical Environment.
- Testing and Assessing System Vulnerabilities.
- Dynamically Assigned Communities of Interest, and Trust Management in a Tactical Environment.
- Correlation, Fusion, Analysis and Visualization of Systems Security Information.
- Secure and Trustworthy Mobile Code in Tactical Operations.

The tactical Army is moving to a wireless, mobile, computing capability within its combat forces. In addition, sensor networks will become an important role of the Future Combat System (FCS). Both wireless ad hoc communication systems and unattended sensor networks need to have a high level of assurance on their information processing and communication capability. The battle field computing and communication system usually operates in dynamically changing environment and is constrained by the limited energy resources. We seek research and solutions to provide the means to accomplish highly assured information processing and communication on the battlefield, in terms of availability, timeliness, confidentiality and integrity. In addition, research on energy efficient computing and communication, system survivability and self healing are of equal importance to the building of a high confidence battlefield system.

Computing architectures are changing. Moore's Law continues to apply and processing power is constantly increasing while the cost per computing cycle continues to drop to the lowest levels ever. Network bandwidth and speed are increasing at a similar rate. The combination of these two events has created a high performance computing capability that is affordable, deployable, and useful in tactical domains. This means, however, that such architectures (e.g., cluster computing or system area networks) are also new targets for an adversary and need to be protected. Protection means prevention of attack, detection of attack when prevention fails, and recovery and/or response from attack. Deploying such measures in the high performance computing and high-speed networking environments thus becomes important. Intrusion detection is one such mechanism in which the Army is interested - but with the caveat that it must not degrade quality of service and must be scalable to match the increasing capabilities of modern architectures.

Many security products are available today to monitor the health and well being of networks and individual systems. Automated tools are needed that fuse the many outputs of these products into an intelligent synopsis of the system security status. Each of these

products can be viewed as a sensor reporting different information. At the next level, the information needs to be fused into a decision. Better visualization tools that enable visualization of the output and facilitate rapid understanding are needed.

Means to provide levels of security appropriate to the threat level are required. Protection of systems to some theoretical maximum threat level will neither be desired or operationally affordable. What is needed is a means and method to scale security measures appropriate to a specific situation and a means to detect when that situation changes - *sufficient security*. Similarly, there is a need for reliable techniques to "measure the degree of security" already employed. In this vein, ideas are sought in the area of security metrics - both for security engineering processes and for composition of systems. For more than 20 years, the security community has attempted to measure assurance with simplistic measures (e.g., digraphs of DoD 5200.28-std or EAL categories under ISO Standard 15408), but these measures have not been successful in the large. More research is needed to understand the current and "to be" security architectures that the Army owns and operates. With the movement to composition of systems from COTS products (systems of systems), there is a need to understand the assurance ramifications of combining untrusted code or combining codes that may have unintentional security side effects.

Research in the area of vulnerability detection and assessment is required. Given systems that have been newly developed or modified, there is a need for the real-time capability to identify and respond to vulnerabilities before they can be exploited. This is closely related to the development of high assurance software. Research in this area is also encouraged.

Solutions that enable the secure exchange of information based on permissions and roles are important. Recent military actions involving coalition forces have brought this point to bear. This is more than a matter of confidentiality - it is an area that requires the ability to separate information or levels of information based on user roles, nationality, and perhaps urgency of situation.

Mobile code has become a concern due to its pervasive use in web-enabled applications that are part of the day-to-day usage patterns of Army employees. The Army both writes and executes code in this category. Active X, Java Script, Java Applets, plug-ins, and other implementations pose a threat from intentional and unintentional damaging side effects. New techniques and procedures are sought that will offer containment of such code, assurance of its proper functionality, and protection from mobile code attack. Each of the paragraphs above has its aspects in the tactical (mobile wireless) battlefield, and ARO is particularly interested in such environments.

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III. SPECIAL PROGRAMS

DOD UNIVERSITY RESEARCH INITIATIVE (URI)

A URI has been a DoD-funded program to perform research and develop technologies in areas of importance to future DoD programs. URI awards are typically on the order of $1 million per year for a basic 3-year period, with additional options for two years for programs demonstrating significant achievement. In this section DoD funded research for two URI programs, Multidisciplinary URI (MURI) and Critical Infrastructure Protection (CIP) is reported..

A MURI center on **Communicating Networked Control Systems** started May 2001 with a team from the Boston University, Harvard University, University of Maryland, and University of Illinois. Its goal is to provide the mathematical foundation needed to fully utilize the new possibilities for the convergence and integration of control and communication technologies. This project is working toward the development to broaden the applicability of multi-system platforms, whose components can interact with one another and with a central controller. It aims to make the control of and interaction with such platforms tractable and economical, by answering questions like: "How many systems can be controlled effectively for every communication channel, controller or processor available?" The number can often be much greater than one, by dynamically allocating resources to the "systems that need them the most". One notable achievement of the team this year has the development and transition of hardware and software for PDA interface/control of robot vehicle formations to the Robotic Vehicles group (Dr. Stephen Wilkerson, ARL/WMRD) at the Aberdeen Proving Ground.

A MURI center on **Adaptive Coordinated Control in the Multi-Agent 3-D Dynamic Battlefield** started May 2002 with a team from the University of California Berkeley, Carnegie Mellon, and the University of Pennsylvania. Its goal is to develop design architectures and provide analytical foundations for the robust adaptive coordinated control of semi-autonomous and autonomous teams of unmanned guided vehicles. The problem is highly complex because of the many challenges faced: (1) the difficulty and complexity in designing control policies for teams of vehicles with fully autonomous and mixed initiative operations, (2) the inability to coordinate a group of vehicles in the absence of global sensing and communication, and (3) the real-time dynamic reconfiguration of paths and plans as new threats emerge. Significant accomplishments of the past year include: (1) Using modified electric Joker helicopters (a lightweight, small-sized radio-controlled helicopter platform capable of carrying a 2 kg avionics/sensor payload), to successfully demonstrate fully autonomous take-off and landing, automatic start up and shut down, and waypoint navigation, (2) Development of a "formation manager" as a high-level agent on top of model predictive control (MPC) to actualize intelligent autonomous heterogeneous helicopter formations, and (3) unmanned rotorcraft vision-based landing in unknown terrain based on fast vision-based target tracking.

A MURI started in late FY2000 on **Mobile Augmented Battlespace Visualization** is led by Professor Avideh Zakhor at the University of California at Berkeley and includes Professor Neumann at USC, Professor Ribarsky at UNC-Charlotte, Professor Varshney at Syracuse University and Professor Lodha at UC-Santa Cruz. The grant investigates a distributed, database system for battlefield visualization of urban environments for the future needs of mobile military personnel. The project generates 3-D renderings of urban environments which are initially constructed and subsequently updated by registering sensor imagery to ground control points and reference imagery with additional inputs from maps and GIS elevation data. Lidar and scanning laser sensor are use to obtain geometries of buildings and images are used to obtain textures of exterior walls. Four dimensional methods (3-D and time) are currently addressing the dyanmics of the target and scene by including time as the 3rd dimension. The resulting 4-D model provides the scene context for interaction, interpretation, and the visualization needs of the users. Specific research issues that are addressed include, but are not limited to, algorithms for geo-registration and tracking, fast and accurate 4-D model construction techniques, portable visualization, dynamic and universal data structures with fast updates for visualization, multimodal interaction, uncertainty representation computation, visualization and validation, and information fusion and uncertainty processing in distributed mobile networks. Results will be verified experimentally by integrating them in a demonstration system. Reviews are held annually at ARL-Adelphi with the participation of the COE Topographics Engineering Center in order to encourage technology transfer.

A MURI program on **Automated Self-Configuring Surveillance Networks** was awarded to a team lead by Pennsylvania State University in May 2001. Pennsylvania State University is joined by Duke University, University of California Los Angeles, Louisiana State University, Cornell University, and University of Wisconsin. The goal of this MURI is to develop the technologies for semi-autonomous self-organizing sensor networks. The concept uses emergent collaboration techniques, which manage the tension between top-down command and bottom-up reaction to the environment in autonomous sensor networks, in order to meet the objective which the surveillance network has been task. Research is being performed in the areas of formal language, finite state automata, sensor data fusion, and communications networking for sensors. Initial experiments have been performed on a robotics test bed.

A MURI center on **Ultra-wideband Communications** (UWB), which started in May 2001, is led by Professor Robert Scholtz at the University of Southern California and includes researchers from the University of California at Berkeley and the University of Massachusetts at Amherst. Since this program was started, the field of UWB communications has received more attention due to the 2002 FCC ruling, which has opened up spectrum for low power UWB applications. The goals of this research are to investigate UWB communications for short-range tactical communications, sensor networks, and integrated UWB tagging systems. Antenna and circuit researchers have been working together on interface definitions between the RF circuitry and antenna in order to assure energy efficient systems. In the systems area, signal acquisition, detection, decoding, and circuit design are being investigated for UWB systems.

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A MURI program on **Space-Time Processing for Enhanced Mobile Ad-Hoc Wireless Networking** was awarded May of this year and is lead by Professor James Zeidler of University of California, San Diego. The purpose of this MURI is to investigate the use of space time coding and beamforming with array antennas in the context of a mobile ad-hoc network. This is a cross layer approach to combine the physical layer communications with the MAC and networking layers to significantly improve the data throughput and reduce probability of detection and interception of the signal by an adversary. Team consists of communications, networking, and antenna researchers from UC San Diego, UC Irvine, UC Riverside, UC Santa Cruz, and Brigham Young University, as well as collaboration with a researcher at McMaster's University in Canada.

A URI CIP program on **High-speed, Wide-area Network Detection, Response, and Analysis** is in its third year at the University of California, Santa Barbara. The project aims at developing a network surveillance, analysis, and response system for high-speed, wide-area networks that will overcome limitations of current systems, including specific effort in the following areas:

- Network monitoring for high-speed networks: The researchers are developing a technique to support network monitoring for high-speed networks based on a traffic slicing technique that, given a model of end-to-end and network-directed attacks, is able to efficiently partition the traffic space and allow for in-depth network analysis on high speed links.

- Highly configurable surveillance sensors: The researchers are developing a highly customizable and dynamically configurable architecture of networks and host-based sensors. Sensors are built from reusable components, making it possible to cover different domains (i.e., networks and hosts) and different environments, (i.e., different operating systems and network services) with a limited development effort.

- Model-based surveillance: The investigators are developing a tool that defines data structures and tools to maintain critical security information about protected networks. The resulting knowledge base enables the monitoring system to identify attacks in the context of the network service infrastructure being protected and to perform effective security analysis.

- Scalable survivable coordination and control infrastructure: The researchers are developing an internet-wide messaging infrastructure that supports aggregation of security information for high-level threat analysis and provides command and control capabilities over the installed network surveillance sensors.

A URI CIP project on **Distributed Immune Systems for Wireless Networks Information Assurance** is in its third year at the University of Maryland. The researchers are developing a program of theoretical and experimental investigation of the fundamental principles that should govern information assurance systems for large

heterogeneous wireless networks, with changing topology and connectivity. Mobile networks with a high degree of self-organization and a great variety of user profiles are emphasized, as are networks with severe communication link bandwidth, limited node processing capabilities, intermittent connectivity, and energy consumption constraints. The research aims at producing robust information assurance systems which can maintain assurance even under high levels of noise and node capture or destruction.

The theme of the program is the development of innovative distributed methods and algorithms that can take advantage of the special characteristics of wireless networks and use them to improve assurance and security, while at the same time keeping the disadvantages inherent in wireless media to a minimum. The researchers are using sophisticated analytical methods supported by selective experimentation and test bed validations to demonstrate and support the claims and results. The following problems are being investigated: automated vulnerability assessment; automated compromised sub-network containment; pro-active intrusion and anomalous behavior detection; automated classification of intrusions and anomalous behavior patters; automated and distributed storage and distribution of intrusion and anomalous behavior patterns; autonomous deployment of passive/active methods for intrusion defense; autonomous deployment of schemes assuring continuous operation at acceptable assurance levels; trade-off analysis between detection performance and false positives vs. complexity and speed of response, robustness and resilience of the proposed assurance schemes; and integration of transmission and traffic flow security with key generation/management and authentication.

There are three **High Confidence Embedded Systems (HCES)**, CIP-funded team efforts. The three teams are led by Professor Lee (UPenn.), Professor Krogh (CMU), and Professor Dwyer (KSU). The 3 teams are composed of 6 prime faculty members each for a total of 18 PI's; in addition there are a significant number of research associates, graduate students, and affiliated researchers from both the national and international research communities. A brief description of each is given below; however it is important to note that the HCES program management strategy has been to leverage these individually funded efforts thru annual collaborative/joint research reviews and workshops. The last review/workshop was held 1-2 May 2004 at CMU in Pittsburgh. Detailed information on the May meeting, and the HCES research initiative can be found at the following website: http://www-2.cs.cmu.edu/~weigand/aro/index.html. This strategy of motivating a collaborative/joint approach to the challenge of enabling the acceptable and principled development is motivated by the fact that there is strong consensus on the various technology need to support a system/software engineering capability for embedded systems. The differences between the three efforts are largely reflected in the methodologies, tools and particular engineering-task focus of the several efforts. As with the first two (2001 and 2002) workshops there was significant participation from industry, other government agencies, and ARO "core-funded" PI's. This HCES program has accomplished significant resource, and intellectual leveraging. Additionally, it has facilitated numerous connections to industry, and other government funded research.

Specification and Verification Center: This center is the home of the HCES effort at Carnegie-Mellon University (CMU). The research challenge of this center is to model large, complex systems and verify the behavioral properties of these systems; this includes issues involving concurrency, distributed implementations, real-time operation, and resource-constraints. To meet these challenges, this HCES effort addresses fundamental issues related to data-structures and algorithms, data and control-abstractions, specification logics, and computational proof techniques. This CMU group builds proof-of-concept tools for model-checking, proof-checking, and a combination of both model and proof-checking. These tools are being applied to a diverse range of applications including: automotive controllers, circuit designs, communication protocols, disk arrays, distributed simulation architectures, file systems, networked systems, robots, security protocols, and spacecraft.

Laboratory for Specification, Analysis and Transformation of Software: This laboratory (SanTos) at Kansas State University (KSU) conducts both theoretical and applied research on a range of topics in programming language semantics, analysis and software engineering. The ongoing HCES funded work of this center is highly leveraged, as is the case for the CMU and UPenn. efforts, thru other governmental funding and previous research advances by these PI's leading to infrastructure elements that allow for continued development of various concepts (tools), and the necessary integration to achieve a more complete part of an engineering solution for enabling embedded systems engineering, and more generally a principled integrated system/software engineering capability. In particular, the previous work of the KSU faculty has led to the development of several tools such as Bandera, and Bogor. Bandera addresses one of the major obstacles to a practical approach to the verification of finite-state software; it bridges the gap between non-finite-state software systems expressed as source code and the "tool" input-languages of several of the available analysis tools (finite-state transition-system descriptions). Bogor is a highly customizable and modular explicit-state model checker designed to provide a robust and efficient tool for finite-state verification of dynamic and concurrent software.

Real-Time Systems Group: The goal of the real-time systems group at the University of Pennsylvania (UPenn) is to conduct research that leads to the development of methods, methods, tools, tool-suites, and/or systems to facilitate the design and implementation of reliable distributed real-time systems. Some of the current projects related to the HCES funding include the development, specification, and analysis techniques for real-time systems, probabilistic-model analysis, schedulability analysis, run-time monitoring and checking, real-time communication, and hybrid systems. As to hybrid-systems, UPenn. and CMU have formed a collaborative working group.

CyLab of Carnegie Mellon University: CMU CyLab combines the efforts of more than 50 researchers and 80 students from the College of Engineering, the School of Computer Science and H. John Heinz III School of Public Policy and the CERT Coordination Center. In the area of information assurance, current research is carried out under four themes:

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1) Available and Secure Computing Systems and Services
2) Available and Secure Network and Communication Infrastructure
3) Secure Access to Physical Devices/Systems and Spaces
4) Guaranteeing Privacy and Confidentiality of Information

CMU Cylab is working closely with Army Research Laboratory on breakthrough technologies to secure and protect the computing and communication capability of U.S. Army. Successful results from the funded research will contribute to the development of a highly assured, efficient, and survivable information system for future combat forces.

Virtual Parts Engineering Research Initiative (VPERI): The specific objective of this research initiative is to facilitate advances in technologies that will lead to improved capabilities to design and sustain/maintain engineered systems. This effort is expected to help insure that future system needs (for system components and/or sub-systems) will be satisfied with improvements in cost, schedule, and quality (as compared to presently, and throughout the life-cycle of these engineered systems). More generally, the results of research funded via this initiative are expected to contribute to enabling advances in the development and integration of infrastructure technologies leading to more acceptable (and/or more capable) computer-based environments for the design, development, and production of engineered systems and their component parts. The scope of this on-going research at the University of Utah and Hampton University includes issues that range from those addressing the creation, archiving, and utilization of design and production data/information to those focusing on the use of virtual design-space to effect a system/part design and production capability. Recently, ARO has funded a small effort at Arizona State University (ASU) to investigate opportunities for enhancing the capabilities of the emerging international "data-standard", STEP for CAD/CAM concerns; and Hampton University has provided some follow-on funding to ASU to ASU to investigate several of the "legacy system engineering issues". Details as to the 4th Annual VPERI Research Review and Workshop can be found at http://www.hamptonu.edu/events/vperc/.

SMALL BUSINESS INNOVATION RESEARCH/SMALL BUSINESS TECHNOLOGY TRANSFER (SBIR/ STTR) PROGRAMS

Real-time Adaptive Classification Environment Using Rules: A Phase II STTR contract on this topic was started in 2003 with Dr. Mark Stevens at Charles River Analytics. The PIs are developing a system called RACER (Real Time Adaptive Classification Environment using Rules). RACER uses meta-features provided by a human operator or inferred from the scene to identify the current operating conditions. Once the operating conditions are identified, the on-line ATR classifier and feature extraction parameters are tuned to maximize target recognition accuracy. The on-line tuning will be rule-based with rules either specified by an operator or obtained automatically through reinforcement learning. A method for combining the output of multiple classifiers using Dempster-Shafer evidence combination is also being explored. Scale invariant features are extracted from multiresolution difference of Gaussian images. On-line matching is performed by computing Scale Invariant Feature Transform (SIFT)

from a novel image and then indexing the closest match in the database. The matches compute an alignment that matches the model to the data. The quality of this match is then used to identify the target.

Hierarchical Multi-Class Target Classification System: A Phase II STTR contract aimed at the investigation, development and implementation of a hierarchical multi-class target classification system suitable for dynamically changing conditions in the battle field was initiated with Dr. Bo Ling of Migma Systems, Inc. and Professor David Cassasent of Carnegie Mellon University. They are developing a new Support Vector Representation and Discrimination Machine (SVRDM) classifiers. Each classifier is a separate classifier that distinguishes one class from all of the rest. This architecture involves a tree structure of classifiers rather than a single layer set of classifiers. The approach uses only a subset of classifiers in any application in traversing a path to a bottom classification decision node. Thus, the number of required calculations is reduced and the classification results are greatly improved. The multiple classifiers are further fused via statistical decision theory for robust performance of overall classification. This new SVRDM approach has the ability to reject non-object inputs. This feature is incorporated into the hierarchical system with the classifier at each node. Since the classes being separated by each classifier are different, different features will be used at the different levels and in the different classifiers of the hierarchy. If successful, this project will make a profound impact on the design and development of the next generation ATR systems found in military applications. The PIs have obtained data from NVESD to develop their models and will use data from AMRDEC to demonstrate the performance of their algorithms.

Automated Target Recognition Using Perceptual Organization: A Phase II SBIR contract on this topic with Dr. B. Ravichandran at Scientific Systems Company, Inc. started April 2001 and ended in FY2004. The research applied perceptual organization algorithmic research to ATR in cluttered environments. Perceptual Organization refers to the ability of a machine vision system to organize detected features, or primitives, in images based on, Gestaltic and other criteria. There have been a number of contributions that demonstrate the importance of perceptual organization for various vision tasks such as object recognition, stereo, motion, image database, building detection and change detection. The Phase II effort developed and demonstrated this technology on static IR data for contour and texture analysis and sequence IR data motion segmentation and tracking. This demonstration is tied to an Army testbed or platform.

Software for Digital Image Management - A Phase II SBIR contract on this topic with Dr. Jill Goldschneider at Insightful, Inc, formerly part of Mathsoft, Inc. started April 2001 and ended in FY2004. The investigation developed image enhancement and segmentation algorithms using curvature-based flow-driven nonlinear partial differential equation imaging models and algorithms, including total variation, level-set, active contour techniques. The Phase II effort integrated these techniques into a Java GUI that interfaces with a database and scripting language to provide man-in-the-loop processing, feature extraction, and analysis of image data. The system was demonstrated on

applications in medical and tactical imaging, and Army applications. This technology will improve the ability to analyze, index and search digital imagery.

Short-Range High Data Rate Wireless Communications: A Phase II STTR contract on this topic started in 2004 with Mr. Triveni Upadhyay of Mayflower Communications Company. The PI proposes to build the physical radio system and networking that will be able to communicate at hundreds of megabytes, but only when the mobile radio is near the mobile base station. In contrast to a voice system, which requires connection all of the time, this system will only pass data when the RF channel allows for a very high data rate, which could be used to download (or upload) large data files, such as video. The approach for the physical layer will be to build a space-time radio that also can perform beam steering in order to provide an anti-jam capability.

Cross-Layer Protocols for Energy Efficient Wireless Sensor Networking: A Phase II SBIR contract on this topic started in 2004 with Dr. Brian DeCleene of Alphatech, Inc. The goal of this contract is to build an energy efficient cross layer networking protocol for sensor networks which will increase the network's lifetime. The medium access control (MAC) protocol will use a unique radio sleep schedule, which saves energy by turning off communications hardware when it is not needed. An energy efficient routing protocol is being developed in conjunction with the MAC protocol.

Biologically Inspired Acoustic Direction Finding for Soldiers: Three Phase I STTR contracts were kicked-off this year on this topic. Dr. Anthony Terrinoni of Antek Corporation, Dr. Josta Agnieszka of AuSim, and Dr. Gail Erten of Innovative Computing Technologies all began work on developing designs for acoustic localization systems that effectively capture the biological employed methods of both inter-aural phase difference (IPD) and inter-aural level difference (ILD). The objective of these efforts are to develop a compact, lightweight, wearable, integrated sound source localization system to be used by individual dismounted soldiers. It is envisioned that this technology will increase a soldier's situational awareness of the auditory battlefield environment and allow for a quick response to enemy threats (e.g. sniper location).

Personnel Detection and Warning Systems for Perimeter, Ambush, and Casualty Detection: This Phase II SBIR will focus on two major objectives. The first is to identify and design a smart detection system around representative sounds and smells in a battlefield environment; and second, is to design a mobile, light weight, networked version of the "ears" and "nose" that can be carried into battle by soldiers. The PIs are focusing sensor development on a set of identified compounds associated with humans which will form the basis of sensor tests in this Phase II. These odors include human odors, cigarette smoke, acetone, hydrogen cyanide, and explosive chemicals. A new sensing technology using DNA as the sensing material will be investigated. New substrates for sensor construction will continue to be studied and methods for more controlled and reproducible application of polymers and dyes to substrates will be explored. Sensor responses across a range of wavelengths will be examined to determine the optimal wavelengths for odor detection and discrimination. The PIs will develop and refine acoustic recognition systems in Phase II that will target the following sounds:

(1) chambering a round, (2) human voice irrespective of word or language, and (3) we will increase the robustness (range of samples) of our current gunshot detection. They also will test all three of these recognition systems for noise robustness using Gaussian White Noise (GWN) and background wind. Dynamic Synapse Neural Network (DSNN) will be used to process the signals and recognize the signature patterns.

IV. SCIENTIFIC ACCOMPLISHMENTS

Tracking Targets Subject to Clutter, Occlusion, Scale Change, and Out-of-plane Rotations
Professor Scott Acton, University of Virginia

This research group from the University of Virginia is designing target tracking methods that succeed in the presence of clutter, scale change of target object, occlusion, out-of-plane rotations and presence of multiple targets. Their computationally efficient methods are based on a probabilistic inferential framework. The idea of this tracking method is to track a target outline by only allowing translation, rotation, shearing, and scaling of a 'base view'. The base view can be obtained from CAD models from an ATR engine at the beginning of tracking. Various views of the target can be generated by applying affine/projective transformations on the base view of the target. Such a target model adds robustness to tracking in severe clutter and significant target scale change. Since the target models involve only 5 (in the affine case) or 8 (in the projective case) scalar parameters, the computation becomes very effective. Stochastic methods such as the Markov Chain Monte Carlo method with some likelihood measure can infer the values of the parameters thus retrieving the target location on a frame of a video sequence. The likelihood measures can be based on edge as well as intensity information of the targets.
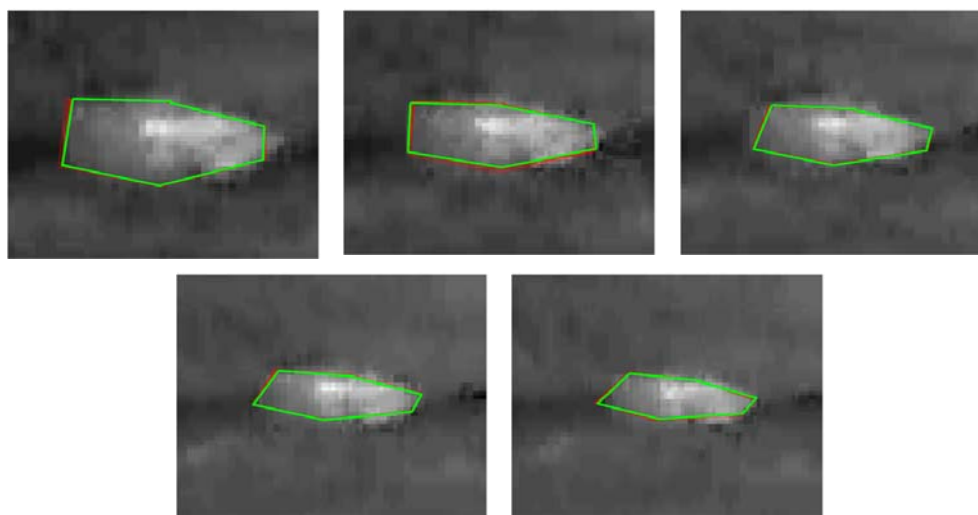
Figure 1. This sequence of images shows the affine active contours (or snakes) in a sequence of images tracking a target through scale change. Track can be maintained through enormous scale changes and clutter.

Obtaining Super Resolution from Low Resolution Frames
Professor Nirmal Bose, Pennsylvania State University

The use of Second Generation Wavelets (SGWs) to attain super-resolution from a captured sequence of low resolution noisy and blurred frames with noise filtering has been shown to be possible without any assumption on grid (sampling lattice) structure. The approach is based on non-separable two-dimensional methods after demonstrating the feasibility in the separable case (based on an already developed one dimensional method). The procedure allows the incorporation of the more general projective camera motion model into the framework, instead of only displacement and rotational models. Professor Bose has performed several simulations that compare the implementation of his algorithm with other related approaches to help illustrate the suitability of SGWs (coupled with hard or soft thresholding) in the task of image sequence super resolution with simultaneous noise filtering.

sample LR frame (low-pass filtered, downsampled,	**original (80x80 crop from Lenna)**	**1-D SGWSR-HT**	**1-D SGWSR-ST**
DTHR bilinear	**DTHR bicubic**	**2-D SGWSR-HT**	**2-D SGWSR-ST**
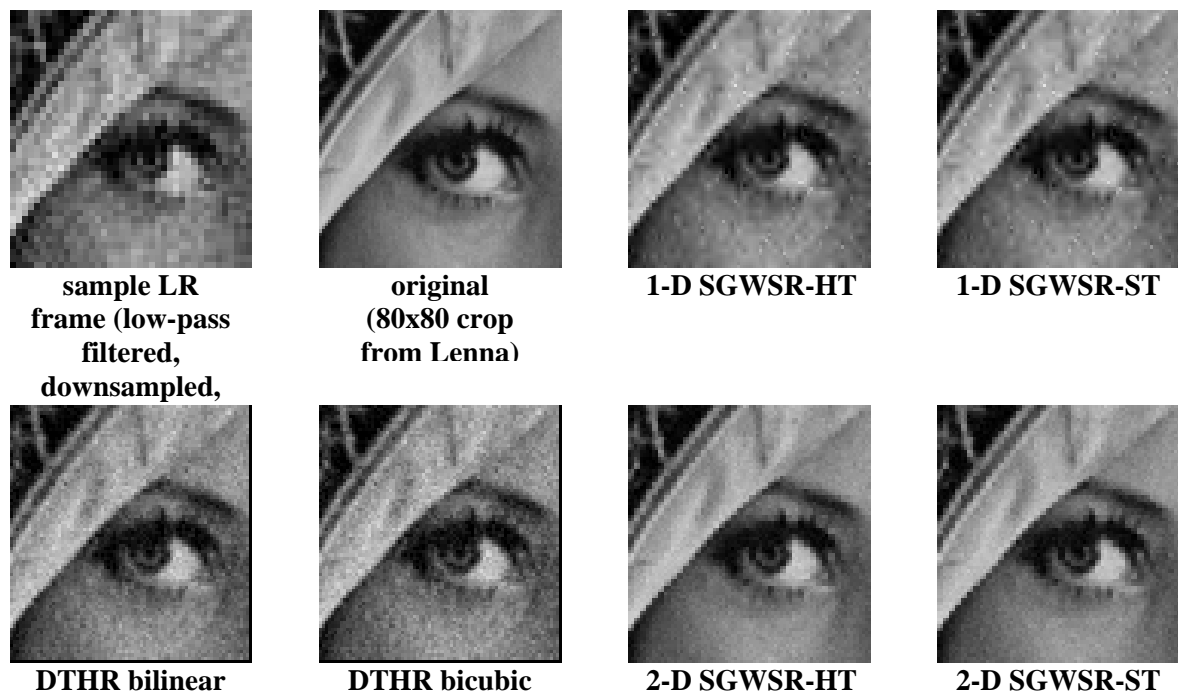
Figure 2. DTHR - Delaunay Triangulation High Resolution
SGWSR - Second Generation Wavelet SuperResolution

Figure 2 shows a set of low resolution (LR) frames, the Delaunay triangulation constructed over the raster generated from three of these LR frames, and frames obtained by updates with the availability of the remaining frames.

Low Energy VLSI Circuit Architectures
Professor Marios Papaefthymiou, University of Michigan

Professor Papaefthymiou's research focuses on the investigation of novel charge-recycling circuit design technologies for ultra-low-energy digital electronics. One of his

research thrusts explores resonant-clocked systems that recycle the charge in their clock distribution networks with the help of novel flip-flops and clock generator circuitry. U.S. patents have been issued for both the flip-flop and the clock generator. The main idea in resonant clocking chips is to resonate the capacitance of the clock network using an inductor, thus setting up an LC oscillation that provides the periodic clock signal. In contrast to conventional, buffered clock networks that send all charge to the ground at the end of each clock cycle, resonant clock systems recover the charge in the clock distribution network and reuse it in subsequent cycles. The clock generator periodically replenishes any energy dissipated on circuit resistors. To demonstrate the energy savings achievable through his resonant clocking scheme, an ASIC chip for the 7-bit Discrete Wavelet Transform was designed. To enable the direct comparison of conventional/ recovering power dissipation, the chip was designed with two clock networks: a conventional one that uses buffer and an energy-recovering one. Through the use of a control signal, the chip can be controlled to operate in one or the other mode. In idle mode (very low input activity), the resonant mode dissipates approx. 60% less energy than conventional. In active mode (high input activity), the resonant mode dissipates approx. 40% less energy than conventional. In active mode, the switching activity of the combinational logic increases substantially in comparison with idle mode. Thus, clock power is a lower fraction of overall power, and resonant clocking saves less chip energy overall.
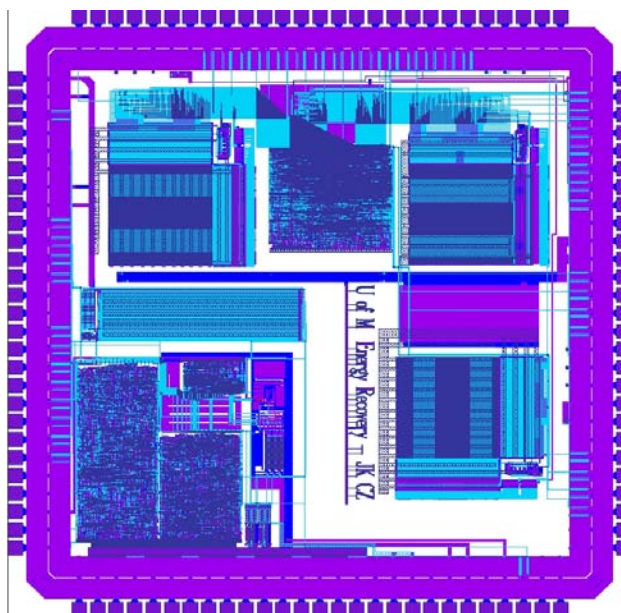
Figure 3. ASIC chip for the 7-bit Discrete Wavelet Transform, 0.25um bulk silicon technology.

Analysis of Text Documents
Professor Insup Lee, University of Pennsylvania (UPenn.)

UPenn has applied "Extended Finite State Machine (EFSM)" formalisms and natural language processing techniques to the analysis of text documents. This work has been

done thru the interdisciplinary efforts of the "formal models and methods" software-oriented faculty in collaboration with the "natural language processing" faculty. Both of these groups have received previous and continued funding from ARO. The proof-of-concept (and value) of the UPenn approach to analyzing documents for explication of reasonable/allowable interpretations of text documents, has been demonstrated using the Food and Drug Administration (FDA) blood-bank regulation policy-documentation. This work was prompted by FDA needs to improve the management of blood-banks, and the need to insure compliance with the regulations. This work has led to a "Material Transfer Agreement" (MTA) between UPenn, the FDA, and the Defense Blood Bank Standards System (DBSS). It is expected that continued work will lead to advances in a number of areas involving interpretations of text documents, including the "requirements documentation" for system/software engineering. This work has resulted in several joint published papers and a public demonstration of this new engineering capability. As cited above, the importance of this work is its ramifications for a number of applications including the troublesome area of collecting, refining, and validating requirements for computer-based systems engineering.

Legacy Systems/Parts Reengineering and/or Remanufacturing
Professor Richard Riesenfeld, University of Utah
Professor Vadivel Jagasivamani, Hampton University
Professor Jami Shah, Arizona State University

As part of the "Virtual Parts Engineering Research Initiative" (VPERI), the collaborating universities: University of Utah, Hampton University, and Arizona State University, adopted a project to remanufacture a "gearbox" provided to Hampton University by the Newport News Naval Shipyard. In a relatively short period of time they were able to work together to produce a new gearbox. The value of this exercise involved the demonstration of the potential return-on-research-investment that is now emerging for the CAD/CAM of legacy systems/parts. A recent annual research review and workshop was hosted by Hampton University on 9/10 August 2004. This workshop involved significant Industrial participation. A significant accomplishment of the ongoing efforts has been to identify specific needs for improved modeling/simulation for CAD, and the coupling of CAD/CAM technologies. As importantly, however, is the interaction with various organizations and the Army community of leading to more general acceptance of the emerging international data-standard STEP for system data packages. The gearbox project was initially reported last year; however, continuing work to refine the methodologies and available technologies has been ongoing. Extensive interactions with Project: HOPE, the Army Tank and Automotive Command, and other DOD organizations have prompted a strong interest in VPERI by the Army Materiel Command (AMC). Gen Kern, CG of AMC, recently visited Hampton University to receive a briefing on the VPERI, and associated partners capability to help solve the problem of providing parts to help maintain Army systems.

Differential Space-Time Modulation for Wideband Wireless Networks
Professor Hongbin Li, Stevens Institute of Technology

The use of space-time coding for wireless communications provides both diversity and coding gain. The use of a differential encoder in the space-time code obviates the need for channel estimation. Professor Li has developed a differential space-time modulation and coding scheme suitable for wideband transmission. This technique uses OFDM to divide the frequency selective wideband channel into non-frequency selective channels and coding across the OFDM channels for frequency diversity. Within this framework, a class of minimum-length full-diversity codes, i.e., linear constellation decimation (LCD) codes, has been constructed with largest coding gain.
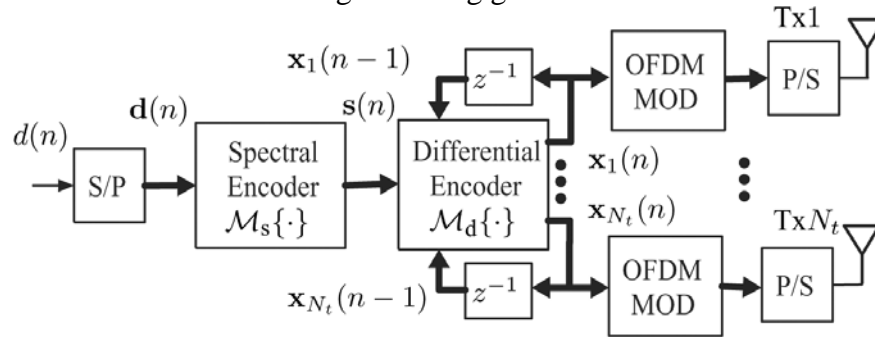
Figure 4. OFDM Differential Space-Time Transmitter Architecture

Spacing-based Channel Occupancy Regulation (SCORE) Medium Access Control
Professor Aura Ganz, University of Massachusetts, Amherst

Different MAC protocols have been proposed to meet various individual requirements for mobile ad-hoc networks, such as quality of service (QoS), multirate, low energy, capacity or fairness. SCORE provides proportional service differentiation for different QoS classes, can support radio with different data rates, provides improved capacity, and saves energy. This is accomplished by adapting the channel occupancy ratio using a variable back-off. The key to the algorithm is the optimized back-off calculation algorithm that is based on packet failures. This algorithm consists of a by a time-continuous hybrid additive increase multiplicative decrease (AIMD) scheme, with a quick recovery mechanism, which is designed in such a way, as to guarantee the system stability and fairness. SCORE has been shown to increase throughput and transmission efficiency as compared to carrier sense multiple access collision avoidance (CSMA/CA).
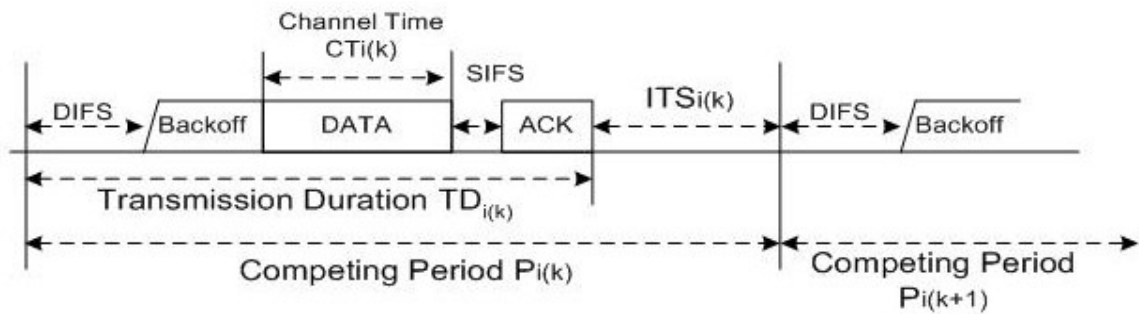
Figure 5. Inter Transmission Spacing Control

Distributed Optimal Sensor Coverage
Professor Francesco Bullo, University of Illinois - Urbana Champaign

Professor Bullo has been carrying out research to develop a set of algorithms for deployment and coverage problems in multi-vehicle networks. He is tackling the multi-vehicle coordination problem in a comprehensive ground-up fashion, developing fundamental modeling tools (what are appropriate motion, communication and energy consumption models?), metrics for performance analysis (when is a configuration or a coordinated motion optimal?), and algorithmic design (what are good coordination algorithms and corresponding information flow protocols?). In particular, one thrust is to design algorithms that are amenable to implementation in realistic networks and that will gently scale with the number of vehicles and devices present in the network. The technical approach relies on a wide variety of tools from control theory, operations research, and computational geometry. His approach is to cast coordination as a stabilization problem with respect to an appropriately designed objective function. Along these lines, he uses concepts from computational geometry and resource allocation to design meaningful objective functions. A second complementary approach is to rely on heuristics and insight in the design of coordination laws; the problem then becomes that of establishing correctness guarantees. He has designed a collection of novel motion coordination algorithms for deployment and dynamic coverage problems. His algorithms provide a multi-vehicle network with the ability to deploy over an unknown area, optimizing various notions of coverage, using only distributed communication. In parallel to the motion control algorithms, he has proposed a first formal notion of spatially-distributed computation. This notion yields estimates on the communication complexity of the motion coordination algorithms.

Coordination of UAV and UGV
Professor Vijay Kumar, University of Pennsylvania

Researchers from the University of Pennsylvania conducted several demonstrations of their autonomous air/ground vehicle coordination technology at Ft. Benning this year. Funded by an ARO-monitored MURI, Dr. Vijay Kumar, Dr. George Pappas and their colleagues are developing techniques to coordinate collections of autonomous vehicles for applications in surveillance. At Ft. Benning, the team flew UAV/UGV missions at

the test site and was able to correlate ground imagery with aerial imagery and coordinate cueing of ground vehicle sensors from air vehicle imagery. This sensor coordination has allowed for a vast improvement of target surveillance accuracy by directing sensors to areas that allow optimal fusion (minimizing covariance) of the air-ground measurements.

Self-Securing Storage
Professor Greg Ganger, Carnegie Mellon University

Self-securing storage aims at developing an intrusion survivable storage system. The self-securing server is able to safeguard data even when the client is compromised. It capitalizes on the fact that storage servers (whether file servers, disk array controllers, or even IDE disks) run separate software on separate hardware. The server-embedded security will not be disabled by any software (even the operating system) running on client systems. Further a self-securing storage server has the capability of actively monitoring suspicious behavior from the user requests, retaining an audit log of all storage requests, and preventing both destruction and undetectable tampering of stored data.
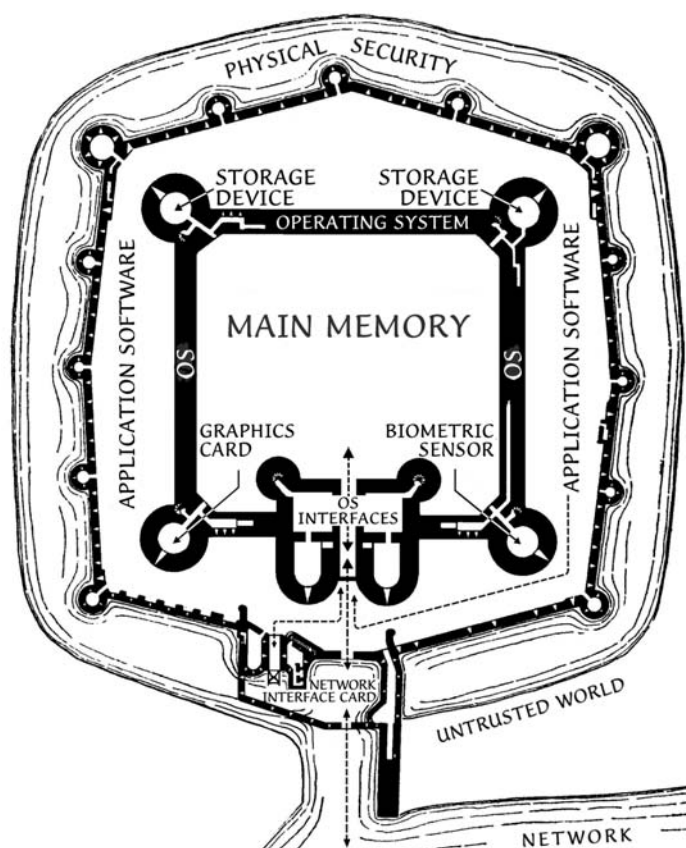
Figure 6. Self-securing storage

SIFF: A Stateless Internet Flow Filter to Mitigate DDoS Flooding Attacks
Professors Adrian Perrig and Dawn Song, Carnegie Mellon University

Distributed denial of service attack victimizes hosts by flooding the target with bogus data packets. Such attacks often render the targeted system incapable of providing its legitimate service. Defeating DDoS attacks efficiently has been a huge technical challenge. The investigators have designed a new Stateless Internet Flow Filter (SIFF) system that aims to thwart DDoS attacks. The SIFF approach enables an end-host to selectively stop individual flows before they can reach the targeted network without requiring routers to keep per-flow state and without requiring ISP cooperation. Under the scheme developed, all network traffic is divided into two classes, privileged (prioritized packets subject to recipient control) and unprivileged (legacy traffic). The network traffic classification allows the privileged flow to be protected from the unprivileged packet flooding. Privileged data channels are established through a capability exchange handshake. SIFF is transparent to legacy clients and servers, but only updated hosts will enjoy its benefits.

Efficient Key Distribution for Secure Multicast and Broadcast
Professors Radha Poovendran, University of Washington

Professor Poovendran has studied the point-to-multipoint or the single sender- multiple receiver model of secure multicast and developed analytical tools for design and analysis of secure multicast. His research results indicate that tree-based key distributions can be analyzed using well founded results from Information Theory and showed that the average number of cryptographic keys to be stored by a user in such a system is characterized by the entropy of member key update process under member deletion (which also includes the voluntary de-registration of a member).

Professor Poovendran also studied energy-efficient secure broadcast problem. He formulated the problem as a cross-layer problem incorporating physical, network and application layer features and was able to map the cryptographic problem to a network problem. The findings of his research indicates that unlike the popular belief, the tree based key distribution schemes might perform worse compared to the unicast based key updates for power or energy-efficient key distribution in wireless ad hoc network. The problem of finding the best key distribution reduces to a decision problem based on energies.

Self-directed Network Intrusion Detection
Professor Paul Barford and Somesh Jha, University of Wisconsin, Madison

Distributed Overlay for Monitoring InterNet Outbreaks (DOMINO) is a multifaceted system designed to support user intrusion data from participating sites to generate intrusion alerts. The system leverages peer-to-peer technology to facilitate collaboration among participating sites. The goal of the DOMINO project is to achieve self-directed, coordinated intrusion detection. One important component in DOMINO is the use of packet monitoring deployed on unused address space through the iSink (Internet Sink)

project. iSink is currently deployed on four class B address ranges and is the first scalable intrusion traffic monitoring for unused address space. The iSink deployment offers a unique perspective on attacks and intrusions and allows more timely alert generation and enables a significant decrease in false alert generation.

A DC-10GHz Linear-in-dB Attenuator in 0.13μm CMOS Technology
Professor Robert Meyer, University of California at Berkeley

A CMOS Attenuator has been designed and fabricated in a commercial 0.13µm CMOS process. Two Π stages are cascaded to achieve more than 35dB of maximum attenuation over a frequency range of DC to 10GHz. Minimum insertion loss varies from 0.8dB at DC to 3dB at 10GHz and remains less than 2dB in the frequency band of DC-4GHz. Attenuation is achieved with a control voltage that varies from 0V to 1.2V and it is linear-in-dB with respect to the control voltage. A DC feedback loop is implemented to achieve input and output impedance matching over the frequency of interest.

575 µm
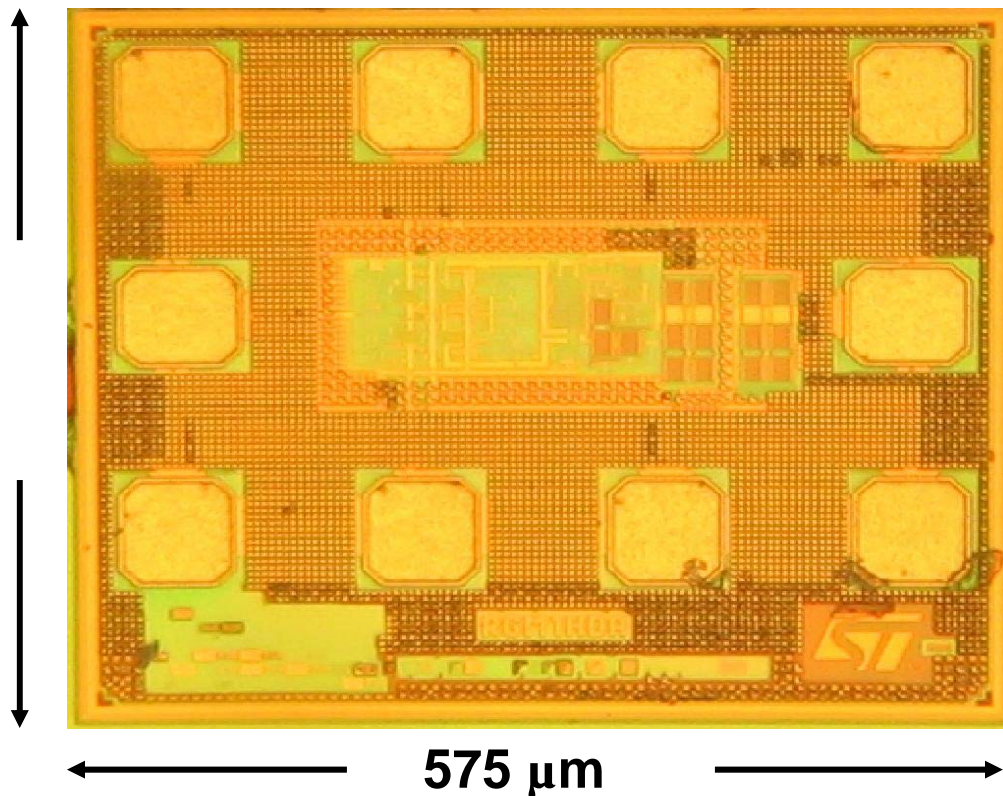
Figure 7.

V. TECHNOLOGY TRANSFER

The CIS Division strongly believes its contract research program must serve the needs of the Army. To accomplish this objective, the Division strives to maintain the highest quality research contracts in the country and to optimize the interaction between Army laboratory and RDEC programs and the CIS Division contractor. Among the methods

used are the evaluation of every division research contract proposal by Army scientists, the personal interaction and visitation of division technical monitors and principal investigators with laboratory scientists, and the conduct of special seminars, symposiums, and workshops for the benefit of Army in-house researchers. The result of these efforts is the transfer of basic research accomplishments into exploratory development performed at Army laboratories and the establishment of cooperative programs between Army laboratories and ARO CIS Division contractors. In addition, it is just as important to encourage transition directly to industry which will build the next generation systems. Examples of these technology transfer and cooperative programs follow.

International Software/System Workshops – The 11th International Monterey Workshop was held on 4-6 October 2004 in Vienna, Austria. These annual international workshops were initiated by ARO and have been successful in facilitating research/technology integration, collaborative research efforts, and joint publishing. Over the past years these workshops have often been co-funded by DARPA, NSF, ONR, AFOSR, and the various international organizations. Each of these workshops has had a specific theme within the general objective of facilitating scientific advances, with the potential to contribute to the emergence of a modern system/software engineering capability. Specifically, the workshop-thrusts have included the idea of providing automated and integrated interactive engineering tools for system/software engineers. The workshop this year focused on "Tool Compatibility and Integration." Importantly, these workshops have contributed to identifying open-research issues, a critical-research path for future investments, and the no-cost/low-cost leveraging of various international research efforts. Details on the 2004 workshop can be found at http://www-step.stanford.edu/Vienna/

ARO Workshop on Information Assurance in Mobile Wireless Networks - This workshop addressed the challenges in providing information assurance in mobile wireless networks that are resource limited. An important characteristic of these networks is that they are ad hoc in nature and have to collaboratively establish and maintain services reliably which must be available at all times in a hostile environment. Apart from the inherent vulnerability of the wireless medium, the resource limitations, intermittent connectivity and need for collaborative communication and computing requires innovative solutions to provide security at all levels in these networks. Unlike the wired networks, which were designed without security in mind from the beginning, we have an opportunity to understand the challenges faced by next generation military wireless networks and start designing secure solutions. This workshop has identified several new research opportunities that ARO should pursue. In addition, several research collaborations were established during and after the workshop.

Embedded-Systems Medical Devices - The ARO initiative in "High Confidence Embedded Systems (HCES) Research has provided several opportunities for technology transfer, including the development of methodologies to contribute to the implementation of an embedded-system infusion-pump for combat casualty care as previously reported. This project involved a joint effort of the Walter Reed Army Institute for Research (WRAIR), the FDA, and several ARO funded universities. This initial project work has

led to several other instances of technology transfer including work on debugging code for a radiation therapy system, and the system requirements-elicitation related work pertaining to formalizing interpretation of text documents. Given, the past contributions to advancing available technologies, and the opportunity for focusing research on safety-critical systems, the ARO research community recently participated in another Embedded Medical Systems Workshop that was held at NSF to advise industry of recent research advances (16-17 November 2004; Washington D.C).

Formation Flying for Unmanned Rotorcraft Vehicles - Researchers from the University of California Berkeley funded under an ARO-monitored MURI have leveraged their work on model predictive based cooperative control of teams of UARs (unmanned rotorcraft vehicles) to computer assisted helicopter formation flying for piloted rotorcraft vehicles. The Berkeley team is in the process of negotiating a cooperative research and development agreement with United Technologies Center and Sikorsky to incorporate their algorithms into the next generation fly-by-wire system proposed for the UH-60M Black Hawk upgrade program.

Adaptive Vibration Modeling and Control For Black Hawk Helicopters - Professor L.S. Shieh of the University of Houston has been investigating adaptive vibration modeling and control for the Black Hawk (UH-60A) helicopter. His particular application involved developing a neural network-based universal optimal vibration estimate model for the helicopter. The goal is to use the estimate for controlling vibration, stall, and increasing reliability and performance. The problem is detailed in the Figure 8. In forward flight, asymmetrical airflow over the helicopter rotor causes large oscillatory forces and moments to be generated on the rotor blades. As the speed of the aircraft increases, the airspeed of the blades advancing into the wind increase, and on the airspeed of the blades retreating from the wind decrease. These opposing forces on the rotor blade cause shear stresses and bending moments; resulting in excessive wear to the rotor shaft, and degraded ride quality. To alleviate this problem without further increasing vehicle weight, active control methods have been proposed. The downside to these methods is that they require accurate model descriptions for the entire flight regime. Dr. Shieh has developed an extremely accurate neural network based estimator, which in turn is used to design a local control to reduce helicopter vibration. The neural network-based approach has been successfully applied to identify the vibration model for the Black Hawk helicopter using the data obtained during rotor testing at the NASA Ames Research Center 80-by 120-foot wind tunnel. As shown in Figure 8, the approach significantly outperforms the least squares approach, which is currently utilized in the Ames Research Center.
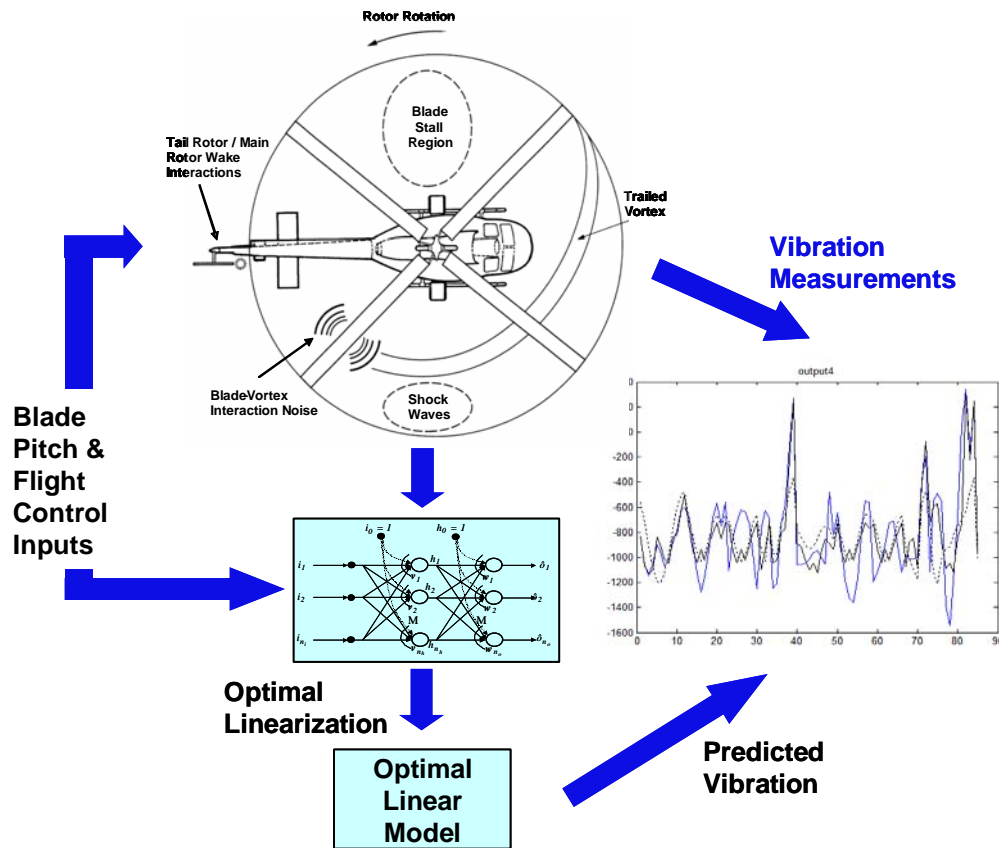
Figure 8.

Professor Daniel Noneaker of Clemson University has had extensive discussions on the design of spread spectrum radio systems with ITT Aerospace/Communications Division. This division of ITT has developed SINGARS and the British BOWMAN Army radio systems. Preprints/reprints of publications from ARO research have been sent to ITT.

Professor Edmund Yeh of Yale University has entered into discussions with Qualcomm and Flarion companies about the resource allocation policies that he has developed under his ARO grant. These companies have indicated that the algorithms developed in this grant can indeed be implemented in practical systems. These algorithms point to certain desirable architectures for integrated resource allocation. For instance, the research results imply that wireless architecture should be streamlined so that data traffic arrival patterns, queue status, and wireless channel conditions are available at a single decision point.

Professor Paul Barford of University of Wisconsin is currently teaming up with ARL to discuss transitioning of the DOMINP project to ARL (Tony Pressley).

COMPUTING AND INFORMATION SCIENCES

Professor Poovendran of University of Washington is working on information assurance on energy constrained wireless networks. This work is of special interest to the Tactical Communication Group of ARL (Greg Cirincione).

Professor Richard Kemmerer of University of California Santa Barbara has transferred his project to several government agencies. The intrusion detection software developed by his team has been installed in DoD agencies including Air Force Rome Lab and Army Research Laboratory. The software is also installed in DoE's Argonne Research Lab.

Professor Sushil Jajodia's current project has a high relevance to the Army Research Laboratory Information Assurance Center's mission. The PI worked closely with ARL staffs during the summer of 2004. Planned activities include: extracting ARL IA operation requirements, validating the developed approach, and developing a preliminary prototype using net-flow data that can be used by the security analysts at Army Research Lab.

Professor Marios Papaefthymiou, University of Michigan, work on low-energy VLSI circuit has produced two patents in FY04 with another pending. Four new technology disclosures were filed with the University of Michigan's Technology Transfer Office. He is interacting with ten companies who are interested in using his low energy dissipating circuit technologies. Cyclos Semiconductor, a start-up launched to commercialize a new class of charge-recovering ultra-low-energy semiconductors, is close to completing negotiations with the University of Michigan for an exclusive license to this technology.

The graph-based Bayesian classifier developed by Professor Larry Carin at Duke University is being used on measured data in the following DoD programs:

1) Wide Area Airborne Minefield Detection (WAAMD) being executed by NVESD
2) DARPA Integrated Sensing and Processing (ISP) program being executed in collaboration with Lockheed Martin.
3) Sensing of unexploded ordnance (UXO) under the DoD Strategic Environmental Research and Development Program (SERDP).

VI. DIVISION STAFF

Dr. William Sander
Associate Director CIS Division
Information Processing, Fusion and Circuits

Dr. Robert Ulman
Communications and Networks

Dr. David Hislop
Software and Knowledge-Based Systems

Dr. Randy Zachery
Systems and Controls

Dr. Cliff Wang
Information Assurance

Cassandra Sanders
Administrative Support Assistant

I. PROGRAM OBJECTIVES

The principal objective of ARO's Electronics Program is to generate new fundamental knowledge of electro-magnetic, photonic, and acoustic devices, systems, and phenomena in order to provide technological superiority to the Army's future force.

This program will identify and solve the Army's critical basic research problems where progress has been inhibited by a lack of novel concepts or fundamental knowledge. Electronics is relevant to nearly all Army systems; therefore, work under this program has application to a wide variety of developmental efforts and contributes to the solution of technology related problems throughout the full spectrum of the Army's "System of Systems." Research under Electronics for the fiscal year 2004 can be divided into four general application areas shown below:

- **Multimodal Sensing** - Sensors and supporting circuitry for detection, identification, and discrimination of battlefield environments, including enemy and friendly elements and their activities. Multimodal includes, but is not limited to, acoustic, seismic, magnetic, infrared, ultra-violet, and RF sensors in both active and passive mode.

- **Ubiquitous Communications** - Multimode and secure communications in all situations and addresses extremely high data rates, transmission over long distances and complex terrain paths, as well as problems associated with short range networked systems. Technology areas include RF, optical, and acoustic transmission. Research includes propagation, device and circuit architectures, and waveform engineering.

- **Intelligent Information Technology** – Technology that enhances the creation and processing of information. This includes hardware and architecture improvements to process information faster, up to fundamental limits, involving miniaturization and new modalities, such as spin electronics, bio-molecular electronics, and parallel optical processing. Also includes signal processing, sensor fusion, and algorithm development for specific hardware implementations.

- **Electromagnetic Warfare** – This involves the use of electromagnetic radiation, from RF to infrared, to interrogate, disrupt, and defeat hostile electronic and threat systems. It includes remote interrogation of electronic systems and disruption of their intended use by electromagnetic signals. It also includes advanced solid state lasers that have very high CW power output (> 100 kW) to defeat incoming projectiles and missiles, or that operate in a specific band to defeat targeting sensors of various threats.

II. RESEARCH PROGRAM

A. General Information

The Army Electronics Program consists of a combination of needs and opportunity driven research. In some cases the needs-driven research projects originates with a highly directed search effort, for example, an STTR project to develop a system to remotely detect riverine traffic for drug interdiction in South America. In other cases the projects arise from the discovery of a unique opportunity that fits a known need, as a project on remote probing of electronic components became useful for detection of IEDs (Improvised Explosive Devices). The pure opportunity research areas tend not to be driven by specifically recognized Army needs. Some can have an immediate indirect impact on Army systems, such as new algorithms and devices that enhance and speed up computer processing. Others can result in future systems requirements once the unforeseen technical capability has been demonstrated and analyzed, for example, new opportunities for room temperature spin semiconductor devices.

The Electronics Division research includes the exploration of new or improved operating principles of electronic devices to provide new performance opportunities and greatly improve performance and reliability of existing devices. Studies of the fundamental limitations of the operating ranges of devices will provide direction for potential improvements. Part of the research effort is the evaluation of phenomena that limit the performance of existing devices. Other phenomena involve the generation, detection, and processing of electronic signals.

B. Trends/Workpackages

ARO's Electronics Division is subdivided into five workpackages or research themes as shown below:

1. Solid State and High Frequency Electronics - This workpackage's objective is to provide novel solid-state electronic devices with high functionality, high efficiency and/or power at ultra-high speeds and frequencies. This research will seek to: discover and develop new materials, advance processing and fabrication science, develop and implement advanced physically modeling and simulation capabilities, and identify advanced device concepts. This will involve conducting research into quantum phenomena, internally and externally induced perturbations, and new transport and optical interaction effects in electronic structures and incorporating these effects into devices and systems with enhanced operation capability. Fundamental research into nano-devices and molecular-level electronics will address issues related to the design, modeling, fabrication, testing and characterization of innovative electrically- and magnetically controlled electronic structures. This research program will include nonequilibrium and dissipative electron processes in low-dimensional device structures, contact and interconnects to nanoscale devices, advanced synthetic materials, devices based upon mixed-mode principles (e.g., photonics, acoustics and magnetics), and heterogeneous (i.e., different materials and device principles) systems. This research

program will have a particular emphasis towards ultra-fast and terahertz frequency electronics and will include a strong component towards sensing science at very high frequencies.

2. Optoelectronics - The objective of the Optoelectronics workpackage is to develop efficient, practical, opto-electronic components for ultra-fast information handling, surveillance, and target ID with an emphasis on visible to infrared emitters and displays in man-portable and autonomous systems. To this end, research is conducted on novel semiconductor structures, processing techniques, and integrated optical network components. This includes the generation, guidance and control of optical/infrared signals in both semiconductor and dielectric materials. Novel light emitting structures based on III-V compounds, II-VI materials, rare-earth doped dielectrics, and silicon nanostructures are investigated. High performance devices and components will be optimized for applications including high-data-rate optical networks. Interfacing of opto-electronic devices with electronic processors will be investigated for full utilization of available bandwidth. Electro-optic components will be studied for use in guided wave data links for interconnections and optoelectronic integration, all requirements for high speed full situational awareness. Emitters and architectures for novel display and processing of battlefield imagery are also important to this work package.

3. Quantum Electromagnetic Devices - This workpackage explores the electrical, optical, magnetic, and acoustical multi-field interactions in various materials and develop novel structures, at the nanometer scale, that optimize the multi-field quantum-effect interactions. Advanced semiconductor materials, such as GaN, GaP, SiC, and ZnO, will be investigated as suitable hosts for accommodating the mutual interactions of electromagnetic and acoustical fields. In particular, electrical, magnetic and optical active elements will be introduced in these materials. Nanoscale characterization will be performed to determine the resulting electrical, optical, magnetic, and piezo-electric properties. Based on these properties, novel quantum-effect device structures, on the nanometer scale, will be designed and fabricated. These device structures will be examined as the basis for unique sensing, data storage, and information handling. This investigation will determine the ultimate performance ranges of field-controlled, quantum-effect nano-devices. It is expected that combinations of electromagnetic and acoustical fields will lead to increased functionality and unique capabilities.

4. Electromagnetics and RF Circuit Integration - The purpose of this workpackage is to enable the development of high performance, low cost, reliable microwave and millimeter wave (MMW) integrated circuits for military applications, and to analyze and apply electromagnetic (EM) phenomena for integrated antenna arrays, multifunctional antennas, and EM power distribution. Emphasis is placed on the high frequency microwave and millimeter wave spectrum for communications and radar, however, specific Army mission related problems at HF, VHF, and UHF are also addressed. Special emphasis is placed on the enabling hardware technology for the digitized battlefield, such as ATR and analog/digital conversion. Integrated RF circuits offer orders of magnitude improvements in systems performance, cost, weight, reliability, and size characteristics. Issues include the coupling of EM radiation into and out of complex

structures; antennas, both active and passive; transmission lines and feed networks; power combining techniques, especially quasi-optical; EM wave analyses of electrical components; EM modeling techniques leading to effective CAD packages for systems such as ultra wideband radar, ground penetration radar, and high power microwaves. Emphasis is placed on quasi-optical power combining to provide the advantages of integrated circuit technology to moderate and high power millimeter wave communications and radar applications, and antenna improvements which have the greatest system leverage in reducing radio and radar power requirements and battery size. Physical constraints imposed by system application, such as the requirement for planar, conformal antenna arrays, are addressed and novel approaches to circuit integration, such as use of the bulk substrate EM domes are explored.

5. Novel Electronic Devices - Projects within this workpackage cover all areas of electronics, with emphasis on areas outside the other ARO Electronics division workpackages. It covers the growth, fabrication, and measurement of electronic materials and devices, as well as, the understanding of surfaces and interfaces. It places particular emphasis on sensors and detectors for Army applications. The detector area concentrates on photodetectors and other imaging devices primarily in the UV and infrared spectral regions. The sensor area covers acoustic, magnetic, seismic, radar, and electric field sensors, all in both active and passive mode. It also contains sensor fusion and networking to enhance the overall sensing capability.

III. SPECIAL PROGRAMS

The Electronics Division supports consortia/center of excellence programs. These programs focus substantial university effort upon topics of critical interest to the Army.

Multidisciplinary University Research Initiative (MURI)

A MURI is a DoD-funded program to perform research and develop technologies in areas of importance to future DoD programs. MURI awards are typically on the order of $1 million per year for a basic 3-year period, with additional options for two years for programs demonstrating significant achievement.

Hybrid Biomolecular and Spin Semiconductor MURI
Professor Datta, Purdue University

In this exciting new field of combining complex proteins in active electronic devices, much progress has come forward since this MURI's inception in 1999. Professor Supriyo Datta is leading a team of researchers at Purdue University, University of Michigan, Brown and Connecticut to study both theoretical and practical device aspects of such hybrid electronics. Specifically, Professor Datta presented models that compute the flow of electrons through individual protein molecules. On the experimental side, a chemist at the University of Connecticut (Professor Robert Birge) has developed the ability to deposit such proteins on electronic devices. His collaboration with Professor

Pallab Bhattacharya at the University of Michigan has made possible the development of photodetectors using proteins to absorb impinging photons in order to detect light. The photovoltaic effect in one commonly used protein called bacteriorhodopsin (bR) has been targeted in this program due its high quantum efficiency (65%), stability, and capability to be used as a memory (storage) device. In fact, Professor Bhattacharya's group presented results of measurements on photodetectors using bR on gold in a GaAs photoreceiver. Another side of this MURI is utilizing ferromagnetic materials to make spin polarized sources of electrons. Arturo Nurmikko of Brown University is working on incorporating such materials with III-V heterostructures to make such devices a reality.
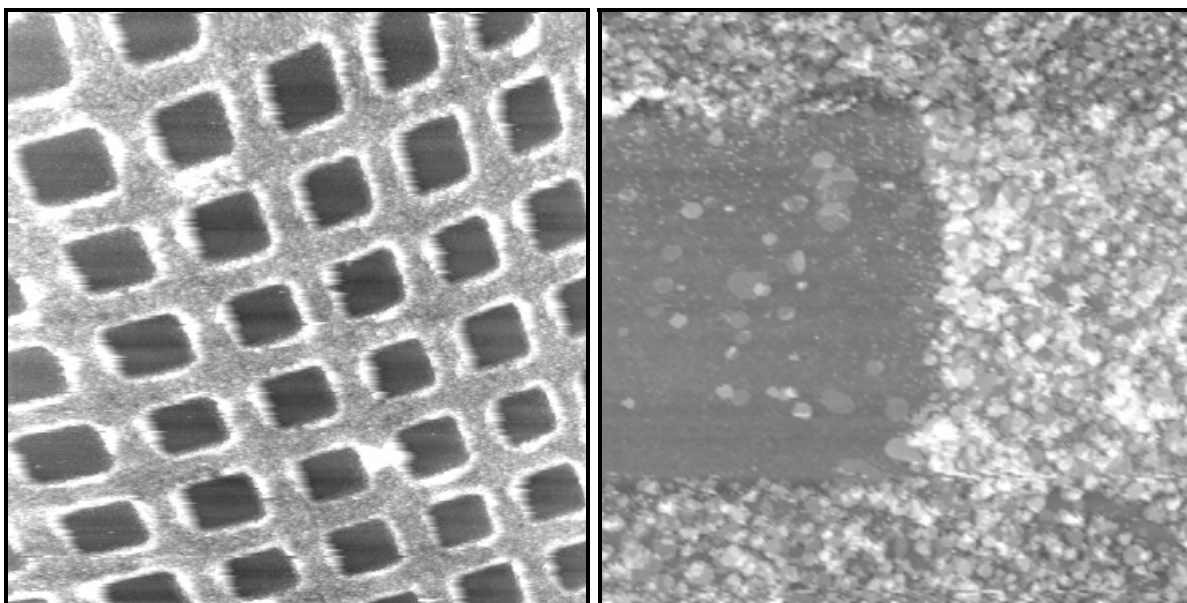
Figure 1. The accurate positioning of oriented Purple Membrane (PM) is required for advanced bio-electronic applications. In (a), a Scanning Probe Microscope (SPM) image (60 µm x 60 µm) of a grid of PM patterned by a new micro-electrophoretic sedimentation (µES) technique developed under ARO-MURI support. The pattern was formed by flowing PM in solution through micro-fluidic flow channels and extends for millimeters along the length of the flow channel. The patterned regions are 9±1 monolayers (45±5 nm) thick. Distortion apparent in the grid is due to SPM piezo-tube hysteresis. In (b), an SPM image taken at higher resolution (11 µm x 11 µm) illustrates the definition achieved by the µES technique. Individual patches of Purple Membrane can be resolved along the inner edge of the pattern.

The most recent accomplishments of the MURI which ends this year are as follows:

1. Professor Reifenberger's group at Purdue has developed a new micro-electrophoretic sedimentation (ES) technique for accurate positioning of oriented Purple Membrane (PM) resulting in patterned regions 9±1 monolayers (45±5 nm) thick.

2. Professor Janes' group at Purdue demonstration of metal/molecule/semiconductor device structures in which the conductivity is higher than comparable metal/semiconductor structures.

3. Professor Nurmikko developed a new means of investigating high density arrays of interacting magnetic particles, concentrating on the half-metallic ferromagnetic thin films of CrO2, which is a very promising material for spintronic devices.

4. Development of detailed numerical models for the analysis and design of spintronic devices including the effects of contact coupling as well as scattering and dephasing processes.

Two MURI awards on **Fundamental Issues in Infrared Detection** were started in 2001. One team of researchers is headed by Professor Pallab Bhattacharya from the University of Michigan, and consists of other researchers from the University of Illinois at Chicago, Harvard University, Arizona State University, and the University of California at Los Angeles. The other team of researchers is headed by Professor S. L. Chuang from the University of Illinois at Urbana/Champaign, and consists of other researchers from the University of Texas. This program will exploit nanoscience to further understand and control material and interface effects in mercury cadmium telluride (MCT) and quantum confined photodetectors. It includes theory, design, materials growth, device fabrication, as well as, small focal plane array fabrication. The fourth review for both teams was held at the University of Michigan on September 27. The meetings were well attended by both the industrial and the government community in this field. One of the highlights at the review was the achievement of a detectivity of 10^{11} for a mid-wave, quantum dot, infrared detector by the Michigan group.

A MURI Program **on Multifunctional Adaptive Radio, Radar, and Sensors (MARRS)** was started in 2001. The MARRS MURI objective is development of new tools, theory, and techniques for multifunction microwave system design, and at the same time production of new methods and materials for graduate-level education in electromagnetics and microwave systems. A multifunction microwave system is one that can receive and demodulate any electromagnetic signal from any direction, return a modulated signal in any specific direction, be reconfigurable to implement a variety of radio and sensor functions, and adapt to its local (ambient) environment to improve signal reception, reject interference, and compensate for multipath effects. Rather than produce a specific design for a particular multifunction system, the basic research performed under this MURI is focused on discovery and development of new concepts and design processes. The educational mission is accomplished through graduate student involvement and publication of research results at conferences, in technical journals, and in books.

The effort has achieved a significant level of accomplishment in technology development, dissemination of results, and educational support. Particular technical developments include: (1) Broadband electrically-tunable barium strontium titanate (BST) based phase shifters and capacitors, (2) Design and simulation tools and techniques for multifunction and broadband RF systems with the capability to model multiple signals and relate circuit parameters to system performance, (3) Exploration of integrated radar and communications based on chirped spread-spectrum techniques allowing simultaneous radar and communications functions in a single RF system, (4)

MEMS-based input and output impedance matching networks for adaptive RF amplifiers, (5) Theory and prototype of a frequency autonomous retrodirective array for combat ID and other sensor applications, (6) Theory and prototype of a multifunctional retrodirective array for sensor applications, (7) Theory and prototype of a retrodirective noise correlation radar with the potential for greatly reduced acquisition time compared to current volume search radar, and (8) Topology and prototype of a high-efficiency Doherty power amplifier.

The remainder of the MURI effort will be used to complete the development of a new methodology for the design of RF and microwave circuits. This will emphasize a perspective that begins with the representation of signals in the time, frequency and statistical domains and develops high level performance measures such as bit error rate. The following tasks are key to implementing this vision:

1. Apply tools to answering basic questions in multifunctional systems.
2. Investigate correlation of different radar and radio signals in a multifunctional system.
3. Investigate and explore dynamic range, linearity, and predistortion requirements.
4. Develop tools for optimization of optimum coding schemes.
5. Develop microwave wideband design practice based on filter design principles.

Results from the MURI have been published in thirty-seven conference presentations and nineteen papers in refereed technical journals. This publication rate is expected to continue through the remainder of the grant. Work is underway on two books related to the MURI research. The first, "RF Design for Wireless" will be authored by Dr. Steer. The second, "Multifunctional Microwave Engineering" will contain contributions from all the MURI PIs. The goal of the second book is to create the underlying foundation for a new course series that exposes seniors and first-year graduate students in electrical engineering to topics in DSP, digital communications, microwave fabrication, components, circuits, and systems design. It is currently anticipated that these books will be published in the fall of 2005.

A MURI Program on the **Science and Technology of Chemicals and Biological Sensing at Terahertz Frequencies** was awarded in FY01 to a multi-disciplinary team led by the University of Virginia. The objective of this research program is *to discover and understand the fundamental physical principles governing the interaction of biological (& chemical) molecules with electromagnetic radiation in the terahertz region of the spectrum.* In addition, a critical focus of this program is *to develop the technology needed to study these interactions and to apply this technology to the design and realization of instrumentation for detecting and identifying biological (& chemical) molecules and their agents.* Achieving these objectives is a vital concern for both military and civilian authorities as they address the potential threat of biological and chemical warfare. Unfortunately, few techniques exist for the rapid detection and identification of biological toxins outside of a laboratory environment. Clearly there is a need for sensitive field instruments that can detect lethal biological and chemical agents on the battlefield as well as in the public environment. *It is the aim of this program to*

develop the science and technology needed to realize such instruments. This program also seeks to integrate sensing sciences with new and novel THz technologies. During the last four years, this MURI effort has been very production and has achieved many first-time achievements in both the sensing science and electronic technology arenas. Noteworthy achievements include: (1) First-time demonstration of THz signature information for DNA, RNA, short-chained oligonucleotides, plasmid DNA, spores, and proteins, (2) Development of state-of-the-art THz components that have been used in projects by the U.S. Army National Ground Intelligence Center, NASA, NOAA, NIST and the National Radio Astronomy Observatory, (3) Established the feasibility of THz remote sensing for detecting clouds of biological spores, and (4) Motivated external collaborative research efforts on annihilation of anthrax spores (*Picatinny Arsenal*) and bio-agent detection technology (*Goodrich Optical Division)*, just to name a few. The high level of productivity is heavily dependent on numerous teaming efforts that often include participation from three or more of the research institutions and always includes multi-disciplinary contributions. This MURI program is dynamically expanding to other institutions, government laboratories, and industry, and it is also having a significant impact on the scientific community. Many of the achievements of this program have been documented in a two-volume book, entitled "Terahertz Sensing Technology," that was published by World Scientific in 2003 and 2004. These books were edited jointly by the ARO program manager (Dr. Woolard) and by the SBCCOM leader of the CB Standoff Detection Group (Dr. Loerop) and emphasize the subjects of (1) *Electron Devices & Advanced Systems Technology*, and (2) *Emerging Scientific Applications & Novel Device Concepts*. Both of these books are illustrated below and are now available to the scientific and technological community as a leading reference to THz electronics.

A MURI Program on **The Science and Technology of Nano/Molecular Electronics: Theory, Simulation, and Experimental Characterization** was awarded in FY01 to a multi-disciplinary team led by Stevens Institute of Technology. The main objective of this research program is to provide a comprehensive theoretical foundation and an advanced modeling and simulation capability for understanding and characterizing the electronic, magnetic, optical and phononic properties of nanoscale elements, devices and systems. This multidisciplinary research effort impressively integrates: (a) efforts developing the underlying physics-based device theory for both nanoscale semiconductor electronics and molecular electronics, (b) efforts developing the large-scale, high-performance computing approaches and numerical algorithms for efficient and effective simulation tools (note that these tools are made available to the broader scientific community via a web-based portal), and (c) experimental efforts that are validating the new models and simulation tools through state-of-the-art research investigations into very high speed nanodevices and extremely novel self-assembled molecular devices; to establish an effective and reliable bridge between today's electronic device theory, modeling and simulation capability to that of the future where molecular devices will be integrated with nanoscale semiconductor devices. During the first four years, the research team has been very production and represents the cutting-edge in nanoscale and molecular electronics research. This productivity is a direct result of the very well organized and integrated multidisciplinary work. This program has a very large number of interactions with DoD Laboratories, industry and to other research institutions and this

is quite noteworthy for a modeling and simulation program. This research is also having a significant impact on the scientific community. The scientific and technical achievements of this program have been used to construct special sessions at each of the last four meetings of the IEEE Nano Conference. The program also contributed to the establishment of new NSF and NASA centers on nanoscience and nanotechnology and has an elaborate portal for distributing/sharing HPC tools to the community. Noteworthy technical achievements of this program include: (1) A new code for designing DNA-based photonic bandgap crystal structures based on self-assembly, (2) Parallelized nanoMOS simulator on a Linux cluster using both PVM and MPI under the Matlab Environment, (3) A 100 times speedup of a Wigner-Poisson simulator, that utilizes a fast path-following algorithm that explains the hysteretic behavior and the onset of oscillations in RTDs, and, (4) Demonstrated classical MIM tunneling in well-characterized alkanethiol nanopores, just to name a few. This program has also generated many external collaborations and technology transfers, which include: (1) collaborations on semiconductor simulation tools with AFRL and CECOM, (2) Interactions with Intel on 3-D simulation of multi-channel tri-gate MOS devices, (3) Collaborations with ARL on molecular conformation models and biodetector applications, and Joint work with NIST on nanopore device fabrication, just to name a few. Future goals include the development of formal activities with major DoD computing centers to share software tools and resources.

A MURI on the **Science of Land Target Spectral Signatures** was awarded to Georgia Institute of Technology (GIT) on 1 July, 2002. This MURI project was awarded as a Cooperative Agreement involving ARL-SEDD and GIT. The MURI will study hyperspectral and polarimetric signatures in the 0.4 to 12 micron spectral regime under complex environmental and terrain conditions. A science based approach will be employed that comprises understanding the signature phenomena, verifying the signature data, and using this information to develop improved Automatic Target Recognition algorithms. The MURI is headed by Mike Cathcart of Georgia Tech and includes members from the University of Hawaii, the University of Florida, University of Maryland, and Clark-Atlanta University. The work is divided into four thrust areas: (1) Hyperspectral-Polarimetric Data collection and analysis, (2) Hyperspectral-polarimetric signature understanding and modeling, (3) ATR, and (4) Information fusion. The third review meeting was held at the Georgia Tech office in Washington, D.C. on October 13 and attendance included personnel from ARL-SEDD, NVESD, AFRL, AFOSR, and industry.

A new MURI on **Human Signatures for Personnel Detection** was awarded to Georgia Tech in June, 2004. This MURI will institute a theoretical and experimental treatment of the basic human signature phenomenology to provide a firm scientific basis for future personnel detection studies. It is anticipated that this scientific base will be used to guide sensor system development and detection techniques of personnel in complex environmental and terrain conditions. Four tasks will be worked on: (1) Human Signature Phenomenology Study to include many different types of signatures, such as: acoustic; seismic; radar (RF to millimeter wave) and passive electromagnetic; active and passive EO/IR (electro-optic and infrared); hyperspectral, etc. (2) Sensor Fusion and

Networking Study to decrease the probability of false alarms and increase the effective range of a sensor system. (3) A New Sensor Concept Study which will exploit the results of the phenomenology study and may include a different modality, and (4) Multi-Sensor Data Collection. The MURI team is headed by Bill Rhodes of Georgia Tech and includes members from the University of Mississippi, Massachusetts Institute of Technology, and the University of California at San Diego. A kick-off meeting was held on August 12, 2004, which was attended by twelve government and industry oversight committee members. Here, it was agreed to investigate the urban environment scenario for personnel detection first. The MURI team was also encouraged to move their STTW (Sense Through The Wall) center frequency from 10 GHz to 2 GHz to get better wall penetration.

A MURI program at Stanford University on **High Average Power Diode Pumped Solid State Lasers: Power Scaling with High Spectral and Spatial Coherence** was started in FY02. This MURI program is headed by Professor Robert Byer and consists of work units led by several researchers at Stanford. This program involves multiple research thrusts with the objective of advancing high power scaling of solid state lasers having a high degree of spectral and spatial coherence. Major goals include: a kilowatt class, cw-laser with quantum noise limited amplitude and phase; a working laser with 1 joule, diffraction limited, and < 1 megahertz line width output; and, power scaling and phase-locking of ultra fast lasers. The use of Yb:YAG gain medium pumped by high brightness laser diodes, with an edge-pumped slab architecture, is being pursued. An important need is the development of laser diodes operating in the 1.5 micron region for in-band pumping of erbium-doped laser hosts. Since high-power diode-pumped solid-state lasers have problems with uniform doping profiles over the length of the gain medium, the researchers are investigating ceramic processing as an alternative solution for achieving 100% quantum efficiency. Fabrication of ceramic gain media with highly-quantum efficiency is being explored to improve doping homogeneity and thermal conductivity. This program is being funded by the Joint Technology Office in Albuquerque, NM.

Other Programs: SBIR, STTR, HBCU/MI, and Other Initiatives

Time Domain Corporation (TDC) has been investigating the use of acoustic waves to detect personnel through walls in an SBIR phase I project. It is expected that such a system will compliment their existing sense-through-the-wall, ultra wideband radar system, and in particularly, be able to sense through *metal* walls. During the Phase I work they successfully demonstrated the feasibility of using acoustics to propagate through common wall materials and wall structures, detect a moving target, and be substantially inaudible in the process. Over a dozen different wall samples were investigated. The left figure shows one of the walls used for the measurements. In a separate measurement using a metal garage door, TDC was able to "see" a moving target on the other side, establishing the validity of acoustic detection through metal.

Enthought, Inc. of Austin TX will develop an integrated information interface for electromagnetic modeling and simulation tools under an SBIR Phase II contract. Under the direction of Dr. Eric Jones, this work will take a suite of efficient and accurate codes

for full-wave electromagnetic analysis such as the Multi-Level Fast Multipole Analysis (MLFMA) algorithm developed under 6.1 ARO support at Duke University and wrap them in a common graphical user interface that simplifies their use and provides a means for end users to script the user interface as well as add underlying algorithms.
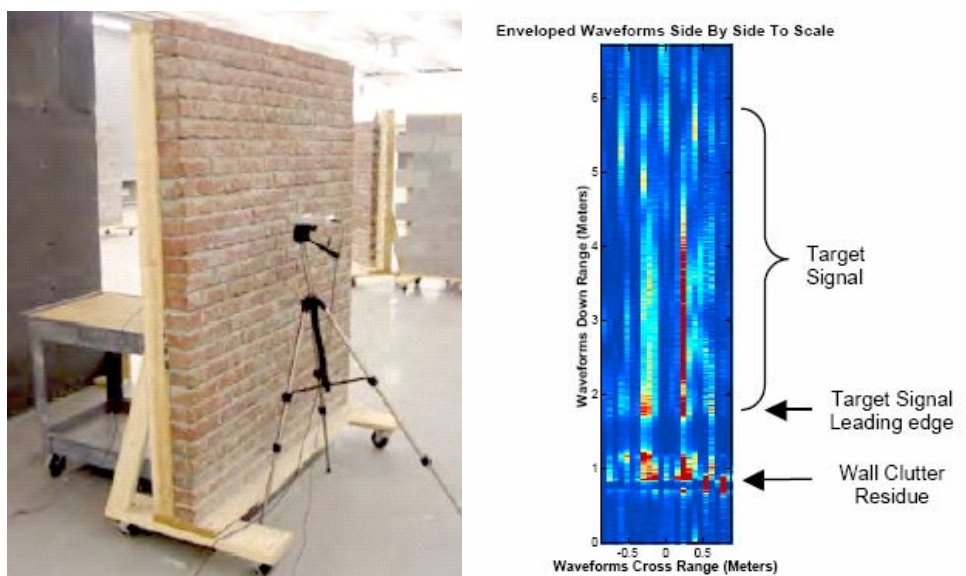
Figure 2. Left – Sample wall (brick) used for propagation measurement. Right – Test data showing feasibility of acoustic detection through metal wall as demonstrated by Time Domain Corporation.
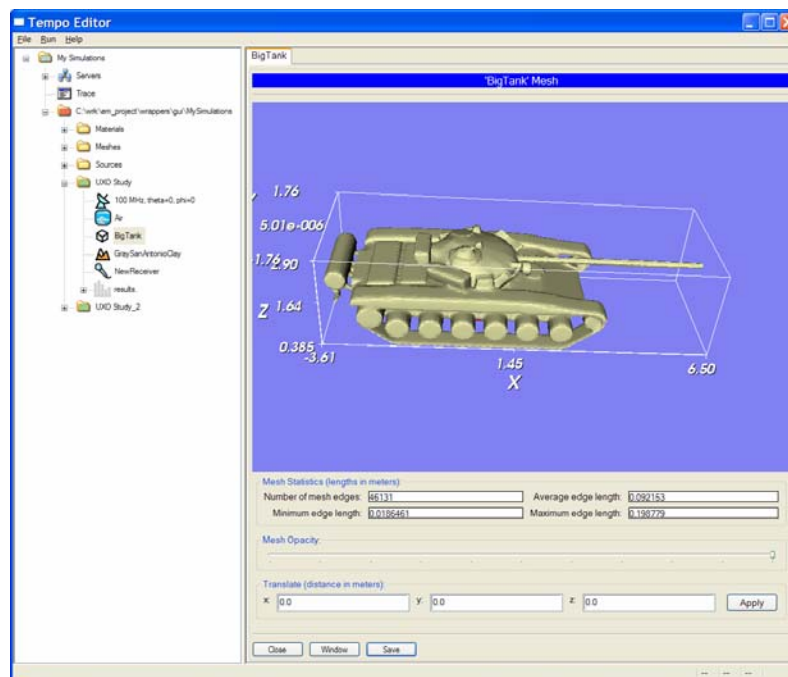
Figure 3. This screenshot demonstrates the integrated information interface for electromagnetic modeling and simulation tools under development by Enthought, Inc. of Austin, TX.

The scripting interface is a key element that provides a capability sorely lacking in most Graphical User Interface (GUI) based scientific software built today – the ability for end users to extend an application's functionality beyond the features that were embedded by the original developers. This scripting capability will be integrated into an intuitive user interface designed by a team including electromagnetic experts, human-computer interface (HCI) specialists, technical writers, and experienced computer scientists. Together they will integrate state-of-the-art 2d and 3d visualization techniques with the best practices in UI design to deliver an application that supports the aggressive schedule for technology insertion into platforms for the Future Force. The proposed research will allow rapid virtual prototyping and enable significant reduction in the design cycle time of communication and radar systems and antennas.

An ARO-managed SBIR project has achieved outstanding success in the development of THz-frequency transmit/receiver components. As a direct result of both the innovative and outstanding accomplishments made by Virginia Diode Inc. (VDI) during their U.S. Army SBIR Phase II project on "Integrated Terahertz Transmit/Receive Modules," they are now the internationally recognized leader in the successful development and demonstration of all the essential components needed for fielding compact and reliable electronic instrumentation in the frequency range 100 GHz through 1000 GHz (or 1 terahertz). Specifically, VDI made unprecedented advances in terahertz(THz)-frequency technology through; the utilization of highly-integrated Schottky-diode fabrication processes, the creation of novel broadband circuit configurations and designs, and by extensive reliance on advanced computer-aided-design and simulation tools. This work

has resulted in a significant list of unique and noteworthy technological accomplishments that have importance relevance for the military, industrial, and the scientific communities. In particular, VDI has developed and demonstrated a suite of diode-based transmit and receiver modules that set new and unmatched standards for performance, ease of implementation, and manufacturability across the entire THz-frequency regime. These collective accomplishments have established VDI as the only commercial source of compact, cost-effective and useful THz-frequency technology. Furthermore, the technology produced by VDI under the U.S. Army SBIR Phase II project have already made major impacts to a broad array of areas including, enhancing compact-range-radar studies at the U.S. Army National Ground Intelligence Center, augmenting high-frequency radar systems at Lockheed Martin Missiles and Fire Control (Dallas, TX), contributing to chemical spectroscopic characterization research at Argonne National Laboratories, enabling investigations of broad-band communications links as a potential solution to the "Last Mile problem" by Telaxis Communications, and improving space exploration capabilities that are under development by NASA's Jet Propulsion Laboratory, just to name a few. Lastly and most importantly, VDI has been the first institution to raise the quality of any THz-frequency technology to the point that it can now be used efficiently and effectively by government, industry and academia as a platform to investigate other technologies and phenomenology within this very challenging frequency regime. The proof of this observation lies in the fact that they are the first and only organization that has ever broadly marketed THz-frequency components and they have accomplished this in the U.S., Europe and Japan. Hence, the outstanding performance of VDI that was produced under the U.S. Army SBIR program will unquestionably make important contributions to science and technology though out the entire world in the future.

Quantum cascade lasers have reached new levels of performance exceeding any other type of electrically injected semiconductor laser in the mid-IR region. The Army Research Office is capitalizing on this research thru development of an STTR program on high power mid-IR lasers. An STTR Phase I Award has been made to Dr. Steve Slivken at MP Technologies where room temperature CW or quasi-CW emission has been obtained at 4.8 microns with power of 325 mW. With further development of strain-balanced structures thru this phase I STTR, improvements are expected in the entire mid-IR range. Infrared countermeasure bands around 4.6 microns are an important application of this technology as well as mid-infrared active sensor systems which are on the horizon for development. Chemical sensors in this band could be made more portable and affordable with such miniature, high-power lasers. Much work needs to be done in these areas and is already underway. MP Technologies in cooperation with Northwestern University's Professor Manijeh Razeghi is already making progress across the mid-IR band from 3.6 to 6 microns (17th Annual Solid State and Diode Laser Technology Review, June 8-10, 2004 at Albuquerque, NM paper by Razeghi, et al.). The goal of this program is to push the technology in commercial arena where Department of Defense systems can readily purchase such lasers for deployment in military systems.

An HBCU/MI grant was started in FY04 with Dr. Kaveh Heidary at Alabama Agricultural and Mechanical State University to develop a framework for the analysis of

electromagnetic wave scattering from a diverse class of targets under ultra-wideband (UWB) impulse excitation that extends beyond the current approach of overlaying narrowband models. Dr. Heidary will conduct a thorough experimental and theoretical/computational investigation of UWB scattering phenomena, focusing on pulses ranging from 0.1 - 10 ns. Mathematical models and computer simulations will be extended beyond current techniques that are based on superposition of narrowband models in order to allow accurate prediction of UWB scattering from a variety of targets. Experiments will be performed to measure the scattering from geometries ranging from simple spherical targets to multiple metal plates and dielectric slabs, and UWB diffraction around corners and knife-edges. The experimental data will be collected using a high-speed digitizing oscilloscope to be purchased under the grant. The experimental data will be used to verify and validate the new mathematical and computer models, and further refine and extend them. Results will be disseminated through publication at major technical conferences and through interaction with personnel at Army labs, particularly the Space Missile Defense Command in Huntsville AL. This work will provide an enhanced understanding of impulse scattering phenomena, enabling new Army applications of UWB technology in communication, precision location, and portable radar, including "through the wall" imaging radar systems.

The Electronics Division started a collaborative research agreement in FY02 between ARL and Lehigh University to perform a series of investigations on the growth, processing, and device analysis of compound semiconductor materials for sensor, display, and laser applications. This program is headed by Professor Thomas Koch, Director of the Center of Optical Technologies (COT) at Lehigh University. There were nine research tasks during FY04 which were performed by COT faculty members and scientists at ARL. This work addressed a number of issues relating to the processing of compound semiconductor materials that are the basis for many opto-electronic devices. In particular, this work involved: use of patterned substrates for MBE growth of GaN on sapphire; novel growth of HgCdTe on Si through a nanometer-thin, strain-relieving oxide buffer layer; development of active matrix arrays for flexible displays and imaging sensors using organic light emitting diode display technology; integration of laser drivers with VCSEL arrays; nano-structured quantum-dots and -wires fabricated from multilayer thin films; development of high efficiency deep UV active regions in group III-nitride materials; investigation of alternative electrode materials for PZT-based piezoelectric actuators and sensors. These topics impact the Army's need for advanced sensors, displays, and lasers for sensing, communications, and chem/bio-agent detection. The effort is relevant to ARL's STO entitled "Sensor Optoelectronic Processing" and to several TPAs that ARL has with AMRDEC, CERDEC and ARDEC.

IV. SCIENTIFIC ACCOMPLISHMENTS

Efficient Modeling of Quantum Well Infrared Photodetectors
Professor K. Ming Leung, Polytechnic University

Quantum well infrared photodetectors (QWIPs) based on the mature state-of-the-art III-V material technology have high intrinsic uniformity, stability and radiation tolerance, and can readily provide two-color detection, temperature sensing, polarization-sensitive detection and general imaging tasks. However, the present level of quantum efficiencies varies from 5 to 25%, which is inadequate for systems requiring higher operating temperatures and high-speed imaging. Professor Leung has been developing an electromagnetic modeling approach based on rigorous modal transmission-line (MTL) solutions of boundary-value problems that indicates that efficiencies of 50% and higher can be achieved by taking advantage of two separate resonance effects. By exploiting the dipole resonance effect, he has designed a two-color detector in a lamellar C-QWIP configuration and a multicolor detector that will serve as a spectrometer. In both the two-color detector and the spectrometer, the shape and selectivity of the individual resonance curves can be predicted and optimized by applying the MTL approach. The second resonance effect (leaky-wave) was used to identify a few practical 3D structures that exhibit absorption efficiencies significantly greater than 50%, with efficiencies close to 100% being theoretically possible. An important advantage of Professor Leung's analytic MTL approach is that it describes the relevant QWIP structures in terms of equivalent electric networks involving transmission-line representations. This network modeling yields a considerable amount of engineering insight that cannot readily be given by other (mostly numerical) methods. In addition, by a judicious selection of modal fields a 10-fold decrease in computation time can be achieved.
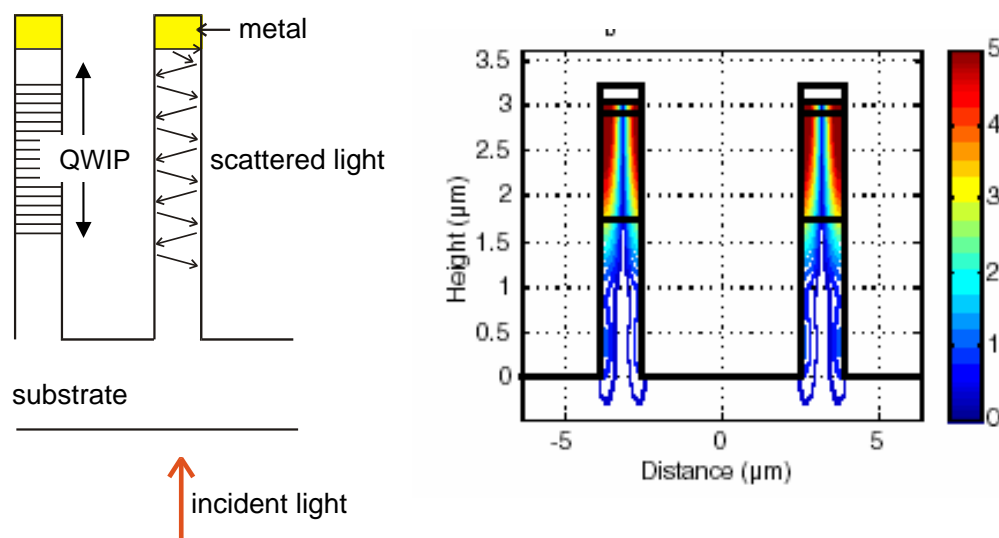
Figure 4. Left - Dipole waveguide resonator structure. Right - results of the MTL modeling technique, indicating high absorption in the QWIP region.

InP Transferred Electron Photocathodes
Professor Piero Pianetta, Stanford University

InP(100) is one of the most important III-V semiconductors, because it has a band gap energy that is suitable for devices such as light detectors for waveguides and possesses electrons of a high saturation velocity which increase the performance of semiconductor devices. Additionally, the most critical step in achieving negative electron affinity in infrared photocathodes is the activation of InP by Cs/O co-deposition. To improve the performance of photocathodes and suppress the mysterious decay of quantum yield that plagues them, Professor Pianetta is investigating the chemical and physical structure of Cs/O layers on the InP(100) surface through photoemission spectroscopy (PES) and Angle Resolved PES. He has been able to show that the time decay of the quantum efficiency (QE) for the activated InP(100) surface may be related to an orientation change of Cs oxide complex on the surface as well as oxidation of the InP substrate. By use of ARPES he can explain the initial decay of the QE by the rotation of molecular oxygen species from a perpendicular orientation (peak A in figure 5) to a parallel one (peak B). On the other hand, after 2 – 3 hours in vacuum the continued decay of the QE can be related to an increase on oxide on the surface as shown in the figure on the right. The high resolution synchrotron radiation measurements were made at the Stanford Synchrotron Radiation Laboratory and the Advanced Light Source at the Lawrence Berkeley National Laboratory. The photon energies varied between 30 eV and 610 eV for observation of the valence band and In4d, P2p, and O1s core levels.
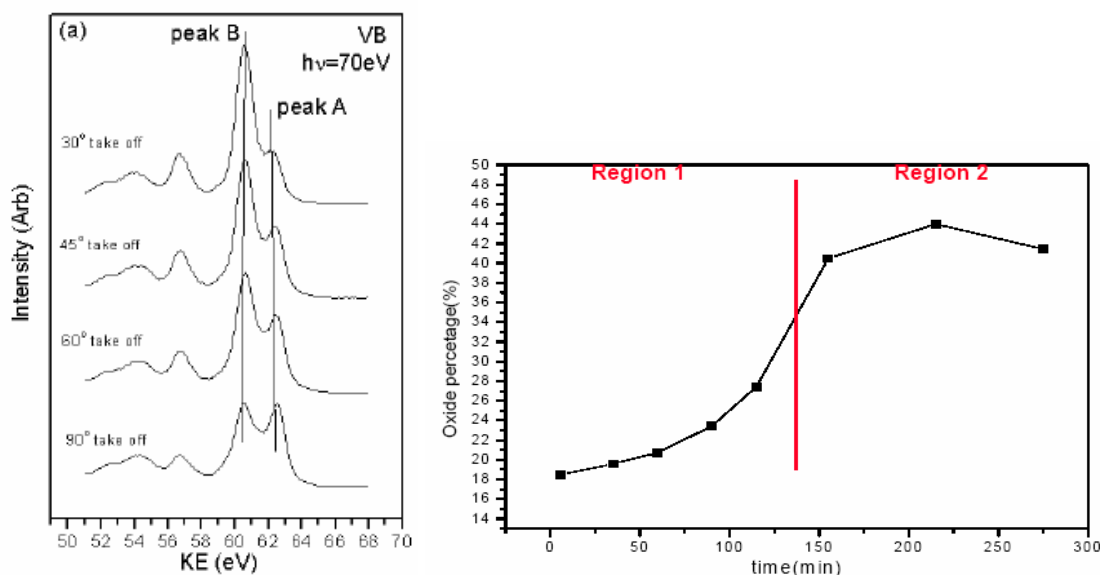
Figure 5. Left - Valance band at different incidence angles after activation.
Right – Substrate oxidation over time

Carrier-mediated Ferromagnetic Behavior of GaMnN Thin Films
Professors Nadia El-Masry and Salah Bedair - North Carolina State University

El-Masry and Bedair have carried out a series of experiments showing that room temperature ferromagnetic behavior in GaMnN thin films is dependent upon carrier occupancy of the Mn impurity band. They demonstrated that paramagnetic GaMnN films can be made ferromagnetic by placing the GaMnN layer within a multilayer structure in which adjacent GaN layers were doped with Mg. In these structures the GaMnN film was not ferromagnetic by itself and the GaMgN layers were electrically p-type. The magnetic properties of the GaMnN/GaMgN heterostructures were found to depend upon the characteristics of the individual GaMnN and GaMgN layers and on the presence of a wide bandgap barrier at this interface. The experiments indicated that the occupancy of the Mn energy band could be altered by carrier transfer at the GaMnN/GaMgN interface. These results provide an explanation of varying reports from different groups of ferromagnetic behavior in wide bandgap semiconductor materials.

Improved UV Light Emitters through Photonic Crystal Structures
Professors H. Jiang and J. Lin - Kansas State University

H. Jiang and J. Lin have succeeded in incorporating 2-D Photonic Crystals (PCs) into III-V nitride UV/blue light emitting diodes (LEDs) and achieved a 20-fold enhancement of light extraction using optical pumping and a 3-fold enhancement using electrical pumping. The PCs, which had a triangular lattice pattern of circular holes with varying diameter/periodicity down to 100/180 nm, were produced by e-beam lithography and plasma dry etching. The formation of PCs reduced lateral guided modes and resulted in a significant enhancement of light extraction in the vertical direction due to coupling into free space. Typically, the quantum efficiency of III-V nitride UV/blue emitters is extremely low and has limited their application. Jiang and Lin have shown that the use of PC structures can enhance the emission efficiency as well as the directionality of UV and blue light emission. Their current efforts are aimed at increasing the light extraction efficiency through a systematic study of PC lattice constant, filling factor, and hole size. (See figure 6.)

p-contact

δ-p-GaN (0.15 μm)

p-Al$_{0.35}$Ga$_{0.65}$N (20 nm)

Al$_{0.2}$In$_{0.03}$Ga$_{0.67}$N(25Å)
/Al$_{0.11}$In$_{0.03}$Ga$_{0.86}$N (25Å)
DQW

n-contact

δ-n-Al$_{0.2}$Ga$_{0.8}$N (3 μm)

AlN (1 μm)

Buffer (25 nm)
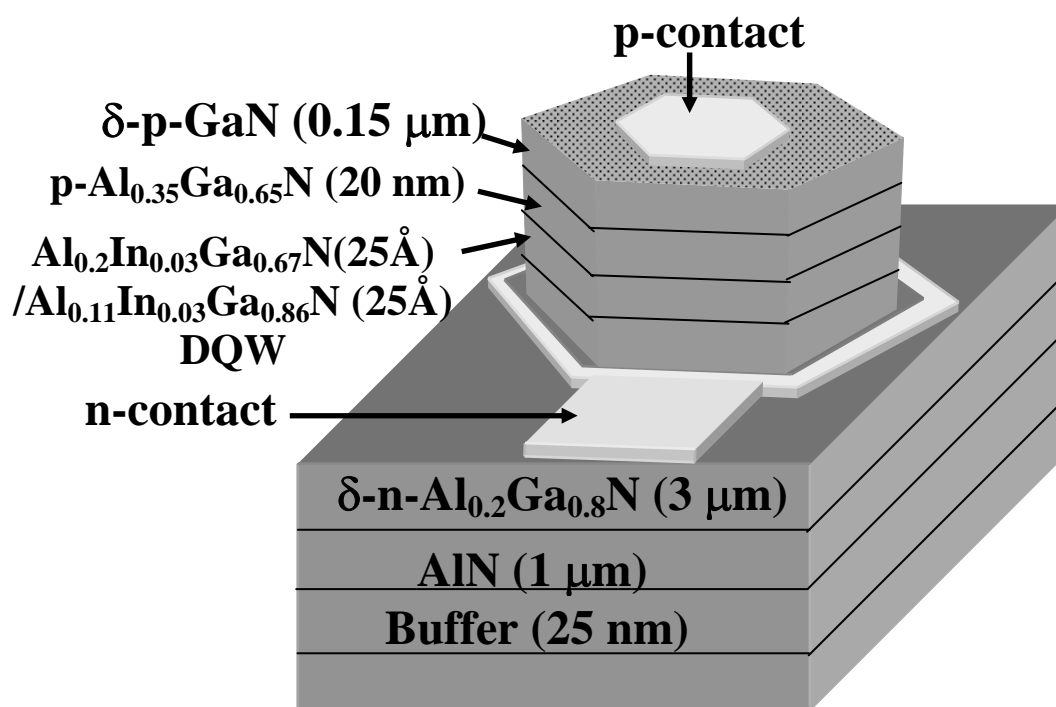
Figure 6. UV LED with photonic crystal surrounding active region.

High Power Single Mode Optical Amplifier
Professor Robert Byer - Stanford University

Robert Byer and his research group have demonstrated more than 120W of CW, single axial mode output from a Nd:YAG slab amplifier. The output is filtered by a high finesse ring cavity mode cleaner to produce a TEM 00 mode to better than one part per thousand. As part of this effort they have demonstrated a low cost fabrication process for manufacturing slab lasers. They have been submitted a patent application based on this process because of its potential for commercial application. The results on the single mode amplifier are important for reducing parasitic effects, improving pumping efficiency, and improving output power in high power solid state slab lasers. (See figure 7.)
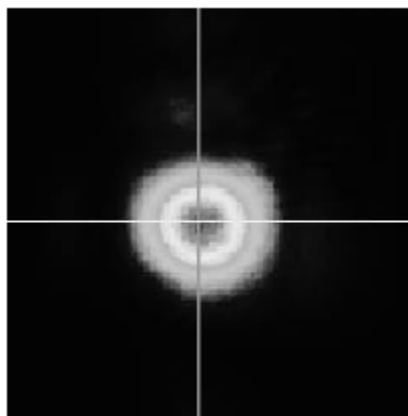
Figure 7. Measured beam profile of single mode, single polarization solid state slab laser.

Novel Design for Nitride-based White Light-emitting Diodes
Professor Ki Wook Kim, North Carolina State University

Kim's research group has proposed a novel design using AlInGaN quaternary material layers as barrier layers in multiple quantum well (QW) structures to realize efficient red light emission. This design is based on theoretical calculations including effects from the spontaneous and piezoelectric polarizations. The strain-induced piezoelectric field dramatically changes the dispersion spectrum of the QW structure.
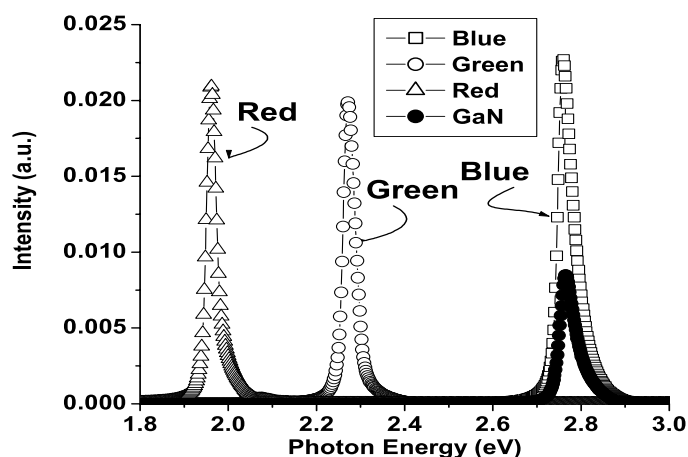
Figure 8. Intensity spectra of red, green, and blue InGaN QWs in the white LED design using AlInGaN as barrier material. Solid dots represent spectrum for typical blue LED.

In their design, three different InGaN /AlInGaN quantum well structures were used to emit red, green and blue light with similar intensity. To achieve high efficiency at each of these colors, important factors relating to the oscillator strength had to be treated. Such light emitting diodes (LEDs) could produce white light and advantageously replace incandescent bulbs or even fluorescent lamps.

High Temperature Mid-Infrared Microcavity Light Emitting Devices
Professor Zhisheng Shi, U. Oklahoma

In 2004 PbSrSe was systematically studied with different Sr composition such as refractive indices and energy bandgaps[1]. The influence on lasing by epi-side up and epi-side down mounting was also investigated to improve heat dissipation. 3 mW continuous-wave (CW) photoluminescence from mid-infrared lead-salt PbSrSe/PbSe multiple quantum wells was observed at room temperature[2]. The most exciting progress was the finding that lead salt quantum well (QW) lasers on [110] orientation will significantly increase the gain[3]. A seventy-degree increase in operation temperature is predicted compared with the conventional [100] orientated lasers. With an improved laser design, room temperature operation of PbSe QW laser in CW mode is predicted to have 10 mW output powers[4]. An ARO funded effort at Pennsylvania State University is developing [110]-laser processing technology needed to make electrically injected lasers.
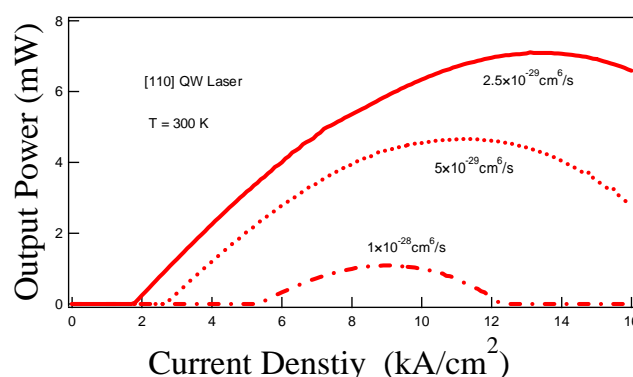
Figure 9. L-I (Light vs. Current) characteristics for Si3N4 clad [110]-orientated QW edge-emitting laser calculated at a heat sink temperature of 300 K for three values of Auger coefficient under CW excitation. These results were simulated based on detailed band-structure modeling.

1. A.Majumdar, H.Z. Xu, F. Zhao, J.C. Keay, L. Jayasinghe, S. Khosravani, X. Lu, V. Kelkar, and Z. Shi, "Bandgap energies and refractive indices of Pb $_{1-x}$ Sr $_x$ Se", J. Appl. Phys., **95**,939 (2004)
2. F. Zhao, X. Lv, A. Majumdar and Z. Shi, "Influence of mounting on continuous-wave photoluminescence from mid-infrared PbSrSe/PbSe multiple quantum-wells", Appl. Phys. Lett, **84**, 125 (2004)
3. Z. Shi, X. Lv, F. Zhao, A. Majumdar, D. Ray, R. Singh, X.J. Yan,[110] Orientated Lead Salt Mid-Infrared Lasers", Appl. Phys. Lett., to be published.
4. X.Lu and Z.Shi, "Theoretical Investigations of [110]IV-VI Lead Salt Edge-emitting Lasers", submitted to IEEE J. Quan. Electron.

High-Speed Tunnel Injection Quantum Dot Lasers
Pallab Bhattacharya, University of Michigan

Since the first demonstration of room-temperature operation of self-assembled quantum dot (QD) lasers about a decade ago, there have been great strides in improving the characteristics of these lasers and their performance currently match or surpass those of quantum well lasers. There are however, unique problems that limit the performance of conventional separate confinement heterostructure (SCH) QD lasers, compared to what is expected from "ideal" lasers with near singular density of states. In the study reported here, unique insights and solutions to these problems have been demonstrated and reliable quantum dot lasers, that surpass quantum well lasers in performance characteristics, have been demonstrated. The characteristics of distributed feedback (DFB) quantum dot lasers have been studied and are described. By utilizing the concepts of tunnel injection and p-doping 1.0 and 1.3 micron quantum dot lasers with high differential gain. Threshold current temperature coefficients (T_0) of infinity, modulation bandwidth of ~25 GHz, alpha-factor less than unity and zero chirp have been achieved.

Temperature Invariant Operation of 1.3μm p-Doped SCH Quantum Dot Laser
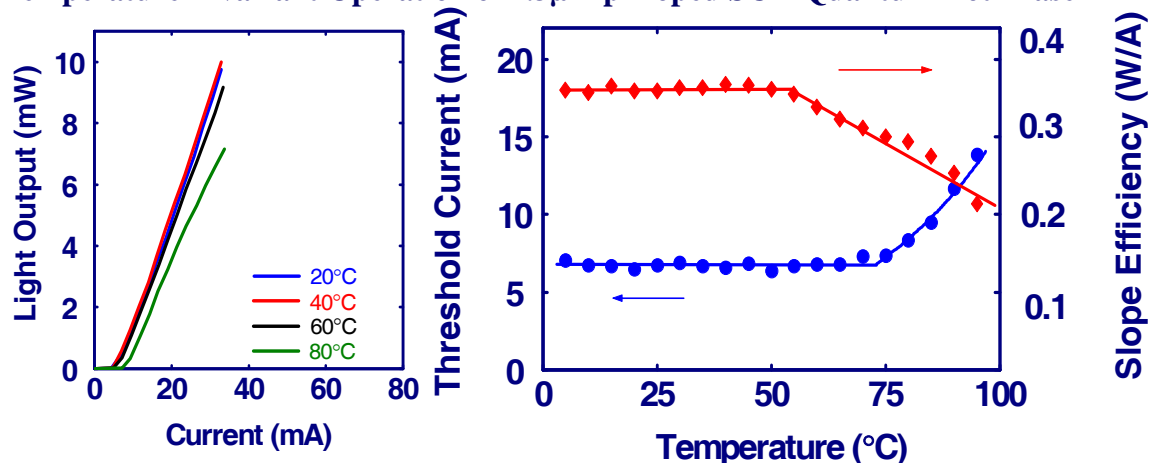
Figure 10. Zero temperature dependence of threshold current ($T0=\infty$) and slope efficiency from 5 to 75°C for p-doped InAs quantum dot lasers.

The Discovery of Photon-Induced Kondo Satellites in a Single-Electron Transistor
Professor Marc Kastner, MIT

Novel research supported by ARO has recently led to the successful measurement of the differential conductance of a single electron transistor (SET) under the irradiation of microwaves. This research is very noteworthy because it has lead to the discovery of microwave sidebands on the Kondo conductance peak of SETs. The basic Kondo effect, which is based upon coupling between an unpaired electron that is localized on a magnetic impurity and a surrounding delocalized electron in a metal, leads to screening of the localized electron's spin by delocalized electrons with opposite spin so that a spin-

zero singlet is formed below the Kondo temperature. Furthermore, the Kondo effect has been demonstrated earlier to manifest itself in SETs (i.e., where the quantum confined region containing an unpaired electron is coupled to the conducting leads in an analogous fashion to that of a magnetic impurity coupled to a host metal) as a series of conductance peaks that are derived by increases in gate voltage. A scanning electron micrograph of a typical SET is shown in figure 11, along with an example of measured Kondo-induced I-V characteristics. Here, each peak corresponds to the addition of an individual electron to the system and the conductance enhancement occurs because
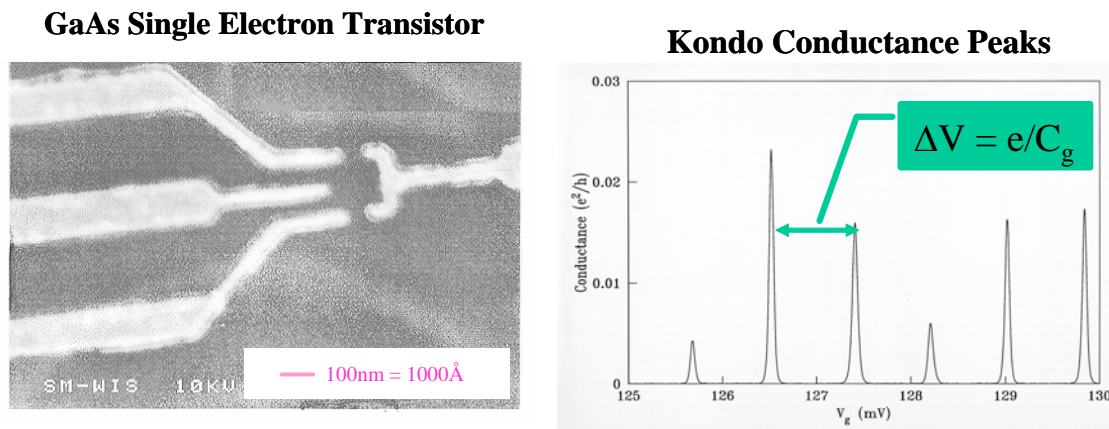
Figure 11

the spin-screening creates a spin-entangled many-body quantum state that extends through the SET from source-contact to the drain-contact. Furthermore, the Kondo singlet in SETs is expected to have an intrinsic time scale related to its width through the uncertainty principle, and the application of a microwave ac voltage between the source and drain of certain frequency is expected to create new peaks at both zero-bias and at certain satellite voltages. For many years the search for this effect has been unsuccessful. However, research from the ARO-supported effort at MIT was able to make a observation of photon-induced satellites in the Kondo conductance of a SET during the last year. This effect was shown to be quite delicate in that the applied frequency must lie in a relative narrow band that is related to the amplitude of the microwave signal and the Kondo temperature so as to preserve coherence and the necessary quantum effects. This discovery is important to the field of nanoelectronics because it will provide valuable insights for the development of new spin-based devices in the future.

Novel Demonstration of a High-Speed Nanotube Transistor
Professor Peter Burke, University of California at Irvine

Research performed under the support of the U.S. Army Research Office's Young Investigator Program has recently led to the demonstration of transistors made from single-walled nanotubes that have the capacity to operate at microwave frequencies. Since the invention of nanotube transistors, there have been theoretical predictions that such the devices have to potential for high-speed operation, but this recent work was the first to achieve a practical demonstration. In this work, carbon nanotubes were grown

from lithographically patterned nanoparticle catalyst sites using CVD and the catalyst pattern was used to align the contacts to the nanotubes – see figure 12. Nanotube transistor function was achieved using the substrate as a back-gate and the device was characterized both at dc and within the microwave regime (i.e., ~ 1-15 GHz). Specifically, low-temperature dc conductances were measured that demonstrated expected quantum mechanical results and S-parameter measurements were used to show gating-induced resonances in the input impedances at 2.6 GHz as shown in the figure 12. These results are significant because they verify that carbon nanotube transistors
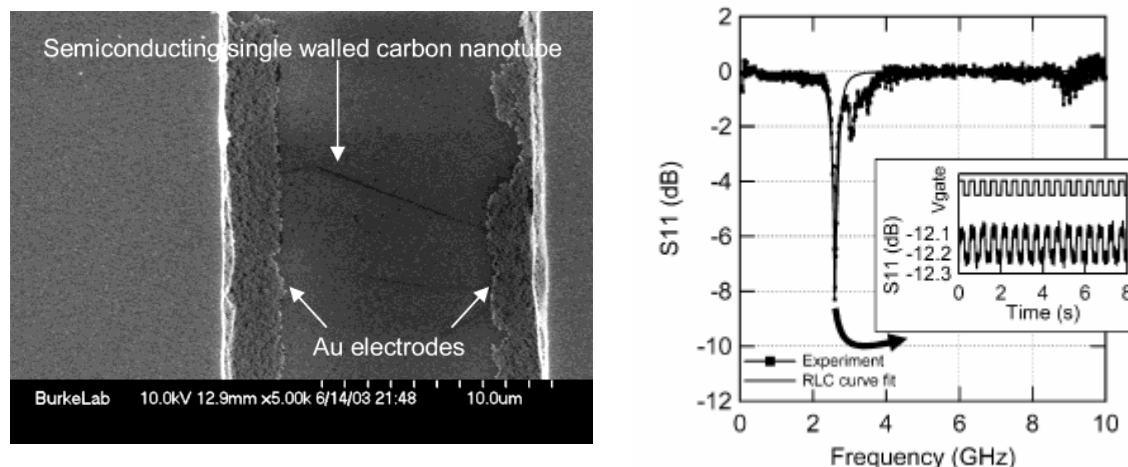
Figure 12

are capable of microwave-frequency operation. Research is now being continued to estimate the operational cutoff frequencies of these devices which can expected to reach speed-limits near the terahertz regime. The present demonstrations, and the future extensions of this research, will be important for realizing high-speed integrated nanosystems. The long-range vision of this work is to achieve prototype nanoscale transistors that are amenable to large-scale integration and application to very high-speed data-processing and communication systems of the future.

Low-Profile Radiators in Non-Periodic Wideband Arrays
Dr. Jennifer Bernhard, University of Illinois at Urbana-Champaign

This work seeks to achieve wideband and dual band operation of a phased array using non-periodic arrangements of wide band antenna elements. Central to this goal is the development of wideband antenna elements for incorporation into the random arrays. The leading candidate is the canted sector antenna previously reported in the literature (J.T. Bernhard, B. Herting, J. Fladie, D. Chen, and P.E. Mayes, "Investigation of wideband low-profile canted antennas for broadside radiation in aperiodic arrays," Proc. 2003 Antenna Applications Symposium, pp. 318-326, Sept. 2003). Unfortunately, the simplest form of this antenna exhibits unstable input impedance and radiation patterns over the desired frequency range. Modifications to the geometry have resulted in much improved broadband performance over the frequency range from 2 GHz to 6GHz, as

shown in the figure 13.
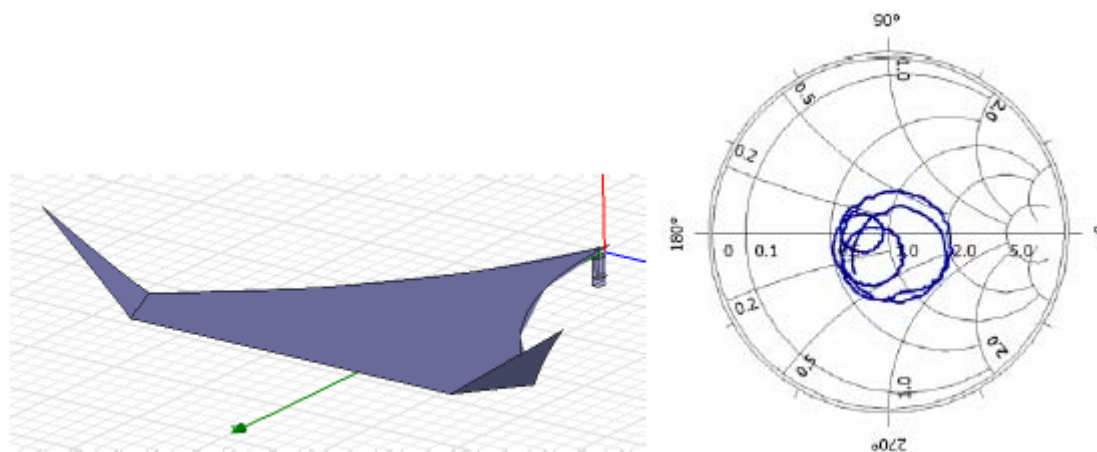
Figure 13. Left – Tapered edge/bent corner antenna element. Right – Measured impedance of the antenna over the frequency range from 2 – 6 GHz.

Recently, the investigator has developed statistical methods for predicting the performance of these arrays, greatly simplifying the design and analysis procedure relative to methods using full-wave numerical simulations. The arrangement of the individual antenna elements can range from regular periodic to completely random. A good compromise between the two extremes is the periodic array of random subarrays (PARS) that provides a tradeoff between the wide bandwidth and low sidelobe performance of a fully random array and the ease of manufacture and analysis of a regular periodic array. Current results have shown that the result is a significantly improved ability to achieve low side lobe levels. These results may be extended to larger arrays with the same rotation pattern.
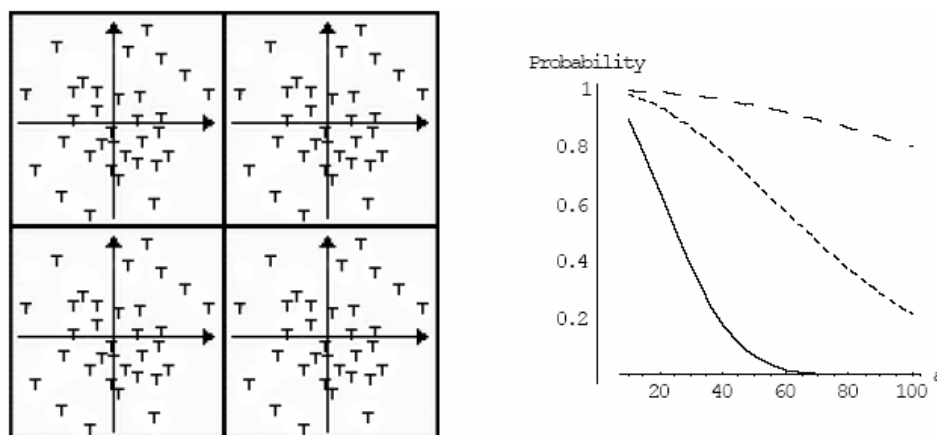
Figure 14. Left – Layout for periodic array of random subarrays (PARS), including subarray boundaries and orientation axes. Elements are randomly placed using a normal distribution. Right – Probability that all sidelobes are less than –13 dB for 3 different values of N in a PARS of 4 subarrays as a varies with frequency. Solid line: N=170. Short-dashed line: N=210. Long-dashed line: N=250.

Work on the possible packaging and arrangement of random subarrays will continue, including investigation of the effects of small numbers of elements and the possibility of recursive rotation arrangements that may duplicate the behavior of truly random arrays.

V. TECHNOLOGY TRANSFER

The Electronics Division strongly believes its contract research program must serve the needs of the Army. To accomplish this objective, the Division strives to maintain the highest quality research contracts in the country and to optimize the interaction between Army laboratory programs and the Electronics Division contractor. Among the methods used are the evaluation of every division research contract proposal by Army scientists, the personal interaction and visitation of division technical monitors with laboratory scientists, and the conduct of special seminars, symposiums, and workshops for the benefit of Army in-house researchers. The result of these efforts is the transfer of basic research accomplishments into exploratory development performed at Army laboratories and the establishment of cooperative programs between Army laboratories and ARO Electronics Division contractors. Examples of these technology transfer and cooperative programs follow.

Professors Sivanathan and Grein at the University of Illinois at Chicago have sent students to the Army Research Laboratory (ARL) and the Night Vision and Electronic Sensors Directorate (NVESD) to work on MBE growth and characterization of HgCdTe. At NVESD they have collaborated in the area of X-ray studies of HgCdTe and CZT substrates to reveal the cause of needle-like defects. At ARL, they have been working to establish standard HgCdTe-pertinent comprehensive databases which include information on material growth, characterization, and detector fabrication and detector performance.

Dr. Mike Cathcart of Georgia Tech and Dr. Paul Gader at the University of Florida, both members of the Science of Land Target Spectral Signatures MURI team, are collaborating with NVESD to explain some of the Wide Area Aerial Mine Detection (WAAMD) hyperspectral imagery. NVESD would like to extend this research to anti-personnel mines in foliage. In addition, NAVSEA Costal Systems Station would like to expand the research to include mine detection in littoral areas. Professor Rama Chellappa at the University of Maryland, also a member of this MURI team, has been working closely with ARL's Image Processing Branch to develop algorithms for Aided Target Recognition of targets in difficult environments.

A Cooperative Agreement was awarded in FY02 between Lehigh University and the Sensors and Electron Devices Directorate of the Army Research Laboratory (ARL-SEDD) to perform a series of studies on the growth, processing, and device analysis of compound semiconductor materials for sensors, displays, and lasers. An important part of this effort involves development of flexible displays based on metal foils and organic light emitting diodes (OLEDs). Professor M. Hatalis has completed the design of a new mask set that enables the fabrication of different active matrix OLED pixel circuits as well as the fabrication of polysilicon thin film transistor circuits suitable for integrated

driver applications. Fabrication was performed on flexible metal foil substrates that were delivered to ARL. Professor R. Blum has been studying image fusion algorithms for Army night vision applications. He has developed new algorithms and provided performance metrics to ARL. Several commercial companies have approached Lehigh University in an effort to obtain a license for Rick Blum's patents on Image Fusion. Professor A. Kahn, from the University of South Carolina, has been providing prototype ultra-violet light emitting diodes (LEDs) to Dr. M. Wraback at ARL-SEDD for evaluation under the DARPA semiconductor ultraviolet optical sources program. The LEDs are second generation device structures that emit at wavelengths below 300 nm. The output powers from these LEDs are the highest reported to date for such devices. Professor Kahn has also provided deep UV LEDs to researchers at MIT Lincoln Labs for tests involving non-line-of-sight communications.

Professor A. Steckl from the University of Cincinnati has been collaborating with Dr. D. Morton at ARL-SEDD on the development of rugged displays based on rare earth ions in wide bandgap host materials. He has fabricated GaN:Eu LEDs that are among the brightest red devices to date. These devices may impact Army needs for full color, flat panel displays.

Professor R. Fork from the University of Alabama has been investigating diamond-sapphire gain elements for high power laser applications under a grant from the Joint Technology Office (JTO). The novel laser structures have potential for improved heat removal under intense laser operation. This project is a spin-off of research under a DEPSCOR awarded by ARO in FY02.

A novel electrically tunable cascaded mid-IR semiconductor light source operating up to 160 K has been proposed and implemented by Professor Gregory Belenky, SUNY at Stony Brook. The wavelength shifts from 2.79 microns to 2.38 microns (~80meV) at T = 80 K as the bias current increases from 97 mA to 418 mA, which provides the record combination of the wide tuning range and low relative change of the bias current. Device design is based on InAs/AlSb/InGaAsSb heterostructure.

The patent "Semiconductor light source with electrically tunable emission wavelength" by G. Belenky, J. Bruno, M. Kisin, S. Luryi, L. Shterengas, S. Suchalkin, R. Tober has been submitted as a result of joint efforts of SUNY team, Maxion Technologies Inc. and Army Research Laboratory (The reference number of SUNY Office of Technology Licensing and Industry Relations is R-7762).
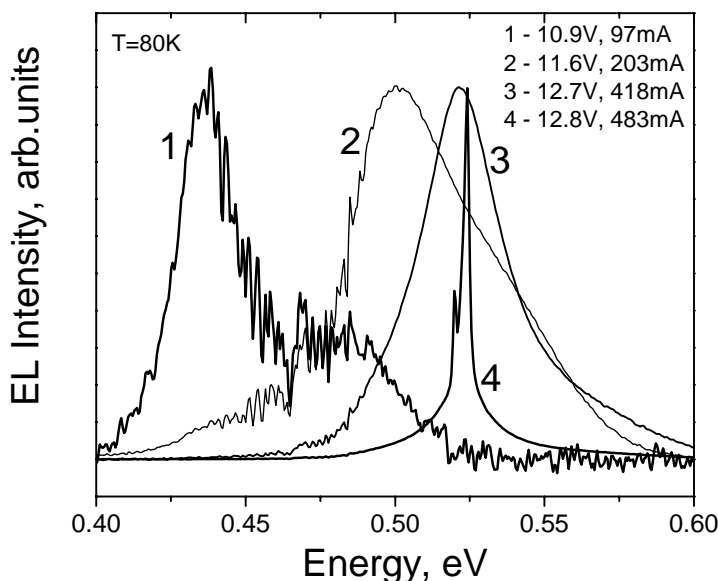
Figure 15. The electroluminescence of InAs/AlSb/InGaAsSb heterostructure laser at different currents.

Professor Globus, of the University of Virginia has made significant inroads on technology transfers in the area of THz-frequency spectroscopic sensing. These activities include collaborations with: (1) *Goodrich Optical Division* to utilize state-of-the-art signal processing software to enhance bio-signatures (Dr. Miller) and she has collected new spectroscopic signature data for bacillus subtillus spores in aerosol form (Dr. Abreu), (2) *IntControl Inc.* (Dr. Ludmila Werbos) to apply neural network based analysis to bio-signatures, (3) *Berkley Lab Synchrotron Center & Lowell University in Massachusetts* where she provided guidance on THz spectroscopy procedures, and *(4) UCSB* (Professor Brown) *and JPL* (Dr. Seigel) to prototype and demonstrate a THz remote sensing system and to understand signature phenomenology.

Professor Ravaioli, of the University of Illinois is making major technology transfer contributions to modeling and simulation in the area of high-speed, nanoelectronics. These technology transfer impacts include: (1) Collaborations with *UCSB (*Professor Allen) and *Sandia National Labs* (Dr. Wanke) where terahertz photoconductivity *experimental results were explained by simulation, (2*) Collaboration activities with *HPti* (Drs. Sotirelis and Richie) managing the DoD PET program, (3) Collaboration with *Motorola* (Dr. S. Egley*)* to understand 3-D charge interface effects on mobility in MOS dielectric stack gate structure, and (4) Interactions with *Intel* (Dr. Surinder Singh) on 3-D simulation of multi-channel tri-gate MOS devices.

Two graduate students from North Carolina State University spent the summer working at the Naval Explosive Ordnance Disposal Technology Division of NAVSEA in Indian Head MD (NAVEODTECHDIV). During their internships they performed preliminary field tests on a prototype system for remote characterization of electric and electronic

devices using electromagnetic waves. Development of the prototype was funded by ARO under the grant "Remote Characterization of Electric and Electronic Devices" to Dr. Michael Steer at North Carolina State University, with supplemental funds from NAVEODTECHDIV and the AMC Field Assistance in Science and Technology (AMC-FAST) activity. In the field tests at Indian Head, the system demonstrated detection of targets of interest at over 13 meters with an RF illumination power of only 5 W. Later in the summer, one of the NCSU students went to Yuma Proving Ground and participated in a field test on a different system, primarily to achieve a better understanding of the terrain and environment that the equipment will be operating in. Work currently is focused on increasing the linearity of the RF illuminator, which will increase the detection range of the system. Optimization of the receive antenna radiation pattern also is under consideration. It is anticipated that further field testing will occur during FY05. Results from the research and field testing are communicated regularly to NAVEODTECHDIV and the CERDEC Intelligence and Information Warfare Directorate (I2WD).

Dr. Ahmed Kishk of the University of Mississippi has an ongoing collaboration with Dr. Steve Weiss at ARL-SEDD and Ron Wardell at TACOM Picatinny to develop dielectric resonator antennas (DRA) applications as a potential replacement for the patch antennas currently used in the ARL Multifunction RF (MFRF) system and for radar fuze applications. This year, Dr. Kishk has extended his interaction with Army laboratories to include investigation of waveguide-fed DRAs as elements of a phased array antenna for the AN/MPQ-64 Sentinel battlefield air defense radar system. The point of contact for this work is Mr. Leon Riley at the Space and Missile Defense Technical Center (SMDTC) Space Technology Directorate of the Space and Missile Defense Command in Huntsville AL.

Dr. Mike DeLisio and Wavestream Corporation (West Covina, CA) have produced a single-chip output stage quasi-optical Ka-band power booster amplifier based on technology created under the ARO-funded FY98 MURI "Quasi-Optic Power Combining" led by Dr. David Rutledge at the California Institute of Technology, which ended in FY02. At the GOMACTech 2004 conference, Dr. DeLisio showed the company's Alpha demo model that consists of two cascaded 256 transistor grids packaged for demonstration purposes with 120 VAC wall power and WR-28 waveguide input and output, shown in the figure 16.

Figure 16. Single-chip output stage quasi-optical Ka-band power booster amplifier developed by Wavestream Corporation.

The unit operates with 13% power-added efficiency at 14 W, produces more than 8 dB of gain over 500 MHz BW at 31 GHz, and with proper cooling can provide output power greater than 20 W. More information can be found at the company website http://www.wavestreamwireless.com/. The company is shipping prototypes and has given briefings at the ARL Sensors and Electron Devices Directorate (SEDD) and CERDEC I2WD. This innovative product was directly enabled by ARO-sponsored basic research.

Workshops and Symposiums

Workshops, seminars, and symposiums are organized and sponsored by the Electronics Division with the purpose of assisting the recognition and stimulating the formulation of planned program thrusts that respond to technological opportunities and Army needs. Army laboratory scientists, as well as, ARO scientists attend these activities. Examples of such meetings include:

- *Request for Sponsorship for the International Semiconductor Device Research Symposium (ISDR'04), Washington, DC, December, 2003.*
- *Symposium MM Amorphous and Nanocrystalline Metals, Boston, MA, December 2003.*
- *Symposium of Light-Emitting Diodes: Research, Manufacturing, and Applications VIII – Part of SPIE's International Symposium on Optoelectronics 2004, San Jose, CA, January 2004.*
- *Organization of the 2004 Advanced Solid State Photonics Topical Meeting, Sante Fe, NM, February 2004.*
- *2004 U.S. ARO Workshop on Nanotechnology & THz Frequency Electronic*

Technology for Application in Advanced Biological Sensing & Characterization, Atlanta, GA, April 2004.
- *Student Travel for the 2004 IEEE Radar Conference, Philadelphia, PA, April 2004*
- *The 20th Annual Review of Progress in Applied Computational Electromagnetics, Syracuse, NY, April 2004.*
- *Workshop for On-Chip Detection and Identification of Chemical and Biological Molecules, Raleigh, NC, April 2004.*
- *ARL-Lehigh University Optics Workshop, Bethlehem, PA, May 2004.*
- *Power Modulator Conference (26th Power Modulator Symposium & 2004 High Voltage Workshop) San Francisco, CA, May 2004.*
- *IEEE 31st International Conference on Plasma Science, Baltimore, MD, June 2004.*
- *OSU International Symposium on Molecular Spectroscopy, Columbus, OH, June 2004.*
- *International Workshop on Nitride Semiconductors (IWN '04), Pittsburgh, PA, July 2004.*
- *Support for the 27th International Conference on the Physics of Semiconductors, Flagstaff, AZ, July 2004.*
- *4th IEEE International Conference on Nanotechnology, Munich, Germany, August 2004.*
- *Proposal for 2004 Antenna Applications Symposium, Monticello, IL, September, 2004.*
- *MWP 2004 –International Topical Meeting on Microwave Photonics, Ogunquit, ME, October 2004.*

VI. DIVISION STAFF

Dr. William Clark
Novel Electronic Devices

Dr. Michael Gerhold
Optoelectronics

Dr. Dev Palmer
Electromagnetics and RF Circuit Integration

Dr. Dwight Woolard
Solid State and High Frequency Electronics

Dr. John Zavada
Quantum Electro-Magnetic Devices

Carla Davis
Administrative Support Assistant

I. PROGRAM OBJECTIVES

The Army operates upon the Earth's surface and its ephemeral natural surface covers. To be successful, the modern Army must be mobile and able to operate and perform effectively and efficiently in operational theaters from equatorial to polar latitudes which may comprise a wide variety of environments, terrain, and weather conditions. Army doctrine has long dictated that commanders know their weather and terrain. The digital battlefield requires detailed and sophisticated information concerning distributed terrain features and conditions. Commanders at all levels within the Army also must be familiar with the environment at large and understand how environmental factors and conditions will impact their operations and the operations of their adversary, and be able to use this knowledge for military advantage. The broad range of terrestrial features, materials, and environmental conditions found around the world can be either a most formidable barrier or a significant advantage for our forces. Within the context of a force-projection Army, these factors are of paramount importance to doctrine, mission planning and rehearsal, effective field operations, systems performance, and logistics. Intelligence planning for the battlefield must take advantage of the environment. An in-depth understanding of individual environments at different scales and the capability to predict environmental effects and behavior for different places and times are essential components for military success in the twenty-first century.

The Army's primary interest in the atmospheric and terrestrial sciences ranges from the near subsurface into the lower atmosphere. The need for research in the environmental sciences stems from the impact that the environment has upon virtually all aspects of Army activities. Despite continuing efforts to develop an all-weather/all-terrain capability, environmental conditions still constrain Army operations. At present, the Army cannot rapidly and efficiently perform the terrain analysis that is required before vehicles and weapons systems can be effectively deployed. The potential impact and leverage of environmental factors must be clearly understood in order to increase existing system capabilities and performance, take advantage of environmental weakness of adversary systems, and optimize the design of new systems. As military technology becomes ever more complex and sophisticated, both systems and operations are increasingly influenced by the variability in natural environmental conditions. Sensor and weapon system developers also must understand environmental effects on system performance to optimize design effectiveness. A capability to remotely sense and interpret the features of the Earth's surface, both natural and anthropogenic, and an automated capability/methodology for the handling and analysis of large aggregates of remotely sensed data are critical requirements for the twenty-first century Army. A continuous dynamic interaction takes place between solid earth materials and the most abundant fluids, water, and air. Therefore, one long-term goal of the Environmental Sciences Research Program at the Army Research Office (ARO), which ties together the individual research efforts within the Atmospheric Sciences Program and the Terrestrial Sciences Program, is the integration of meteorology, hydrology, and geomorphology. In particular, there is a need for the development of first-principle physical/chemical processes models, better technologies and methodologies for environmental characterization and prediction, and computer-based techniques for monitoring,

modeling, and simulating the natural environment. Special emphasis is given to the need to better understand, model/simulate, and predict those environments/conditions that are most dynamic or restrictive to systems performance or military operations.

II. RESEARCH PROGRAM

ATMOSPHERIC SCIENCES

A. General Information

Motivation - The Army has the responsibility to provide fundamental knowledge of the atmospheric boundary layer over land to all U.S. armed services since that boundary layer is the primary theater for Army operations. Intelligence preparation of the battlefield depends on a full knowledge atmospheric conditions and their effects on operations, weapon systems, and the soldier. It requires an ability to estimate atmospheric details at specific locations and a future time to maximize strategic weather advantages. Knowledge of the atmosphere and its effects on soldiers and sensor systems are essential for command and control as well as visualization of the battlefield at all echelons. The Army lead for chemical and biological defense requires detailed knowledge of the threat once it is induced into the air. In garrison, Army training and preparedness depend on accurate representation of atmospheric test conditions and on physically correct portrayal of atmospheric processes and effects in simulations.

The research program is broadly based to address the wide spectrum of conditions and influences of the atmospheric boundary layer on Army operations and systems. It is divided into three general research areas of the boundary layer problems:

- Atmospheric Effects on Signatures and Communication;
- Characterization of the Atmosphere at High Resolution; and
- Management and Application of Atmospheric Information.

<u>Atmospheric Effects on Signatures and Communications</u> **-** Success on the battlefield will depend, as much as ever, on superior sensing systems, the ability to detect before being detected, advanced target recognition capabilities, and reliable communications. Because the atmospheric environment strongly affects performance of almost all communication, detection, and recognition systems, a clear understanding of environmental effects, along with tools for accurately assessing these effects, is essential. This knowledge is needed for sensor and communication system design and simulation, battle planning, and interpretation of sensor data on the battlefield. Conversely, opportunities to use electromagnetic and acoustic systems to sense the atmospheric properties providing characterization of the battlespace, which are vital to battlefield weather awareness.

Both atmospheric structure and terrain properties affect acoustic signals in the atmospheric boundary layer, causing detection and recognition ranges to vary

dramatically between different terrestrial environments as well as over diurnal cycles. Current EM and acoustic propagation models can account for many factors but the models are generally two-dimensional and do not accommodate complex terrain features or urban environments. Modeling large-scale atmospheric turbulence and its effects on sound waves is a challenging area of research.

The goal of future research is to better understand how the different wave propagation effects vary with time and location so battlefield operations can be optimized. Verified prediction techniques and models allow planners to define system capabilities and may suggest techniques to mitigate atmospheric effects. Time and distance scales appropriate to typical battlefield engagements are seconds to minutes and meters to kilometers, respectively

Characterization of the Atmosphere at High Resolution - The atmospheric boundary layer is the primary part of the atmosphere where the Army lives and breathes and where sensor systems operate. To attain information superiority, conduct precision engagement, and dominate battlefield knowledge, the current and future state of the battlefield atmosphere must be known at very high resolution.

The diurnal evolution of the atmospheric boundary layer over land shows a very dynamic interaction of local and regional heating and cooling, winds, moisture, turbulence, terrain, and larger scale forces, which change throughout the day and night. These factors affect battlefield environments on scales from millimeters to tens of kilometers and microseconds to hours or days. The highest priority use of this knowledge is to protect the force from the effects of CB weapons with highly accurate predictions of the mean and fluctuating concentration of the agents in real time. The same science and technology can be applied to induced or natural obscurants and applies to homeland defense issues.

Knowledge barriers exist at the high-resolution measurement of the four-dimensional dynamics of the atmospheric boundary layer at the various scales affecting operations or propagation. Current parameterizations of the physical processes inadequately provide detailed, trustworthy representations of the on-going processes. Knowledge of boundary layer interactions with larger scale motions and with terrain is only in its infancy.

Management and Application of Atmospheric Information - Providing useful atmospheric effects information to the soldier and decision-maker is a goal of the Army's atmospheric sciences effort. The information needs of each user may be very different and in different forms. Nevertheless, the path from data to information must have a fundamental scientific basis. The science issues behind the information management include an ability to obtain data from multiple sources, friendly or adverse, quantitative and qualitative; fusing the data into a comprehensive representation of the present and future atmospheric state; understanding of the uncertainties of the data and its effect on the application; and communicating the complex four dimensional atmospheric in the language and application of the user.

Investment – For FY04, a total of $1,033 thousand was spent to support research programs in the Atmospheric Sciences area. This amount includes $182 thousand for support through the Defense University Research Instrumentation Program. The bulk of spending was the $851 thousand in the Army's portion of Defense Research Science basic research funds of the program. Of that amount, approximately $500 thousand was spent on studies of atmospheric dynamics, and the balance was spent on studies of acoustic and radar remote sensing of the atmospheric boundary layer. Supplemental funding of $25 thousand from Defense Threat Reduction Agency helped maintain support for analyses of field program data. Current planning for FY05 indicates an expenditure of about $1 million in this area.

Interactions – This research program is closely coordinated with research and development programs in the Battlefield Environments Division of the Army Research Laboratory. Interaction with Army scientists and engineers occurs through personal contact in program reviews, planning meetings, and joint workshops. In FY03 and looking forward, a coordinated, joint participation in the JointUrban 2003 field program brought a pair of matched Doppler lidars to measure wind fields interacting with urban structures. Analysis and interpretation of those data continues through participation of the ARL scientists in the peer review and Army relevance evaluations of proposals and scientific liaison or cognizance of the research in progress. The program is coordinated with other DOD programs through the Atmospheric and Space Sciences Scientific Planning Group; with professional societies through meetings, planning groups, and workshops; through participation in OFCM Joint Action Groups; and through participation and review of DoE, NOAA and NSF agency programs

B. Thrusts and Trends/Workpackages

Boundary Layer Meteorology: Research thrusts with highest Army priority include the diurnal evolution of the boundary layer. A particular interest is very stable boundary layers, and the transitions of stability, which occur with sunrise and sunset. The CASES-99 field program near Leon, Kansas in October 1999, investigated these dynamical states and their evolution. The JointUrban 2003 field program in Oklahoma City, OK is a landmark effort in study of urban effects on dispersion of materials released in a city. The paired lidar program conducted by the Army provides the first-ever volumetric measurement of wind flow into, through and behind urban structures in both day and night conditions. Analysis of the 23 GB of data and understanding the evolving physical processes and developing models of the processes remain a difficult challenge. The ARO research program has emphasized analysis and interpretation of the data from all sources by its sponsored researchers.

Remote Sensing: Future research will give high priority to measurements of fields of wind, moisture, and temperature in the atmospheric boundary layer at high time and space resolution. Significant progress has been made through the development of high resolution Doppler LIDARs, phased array profilers to observe the turbulent structures and winds, improved FM-CW radars to identify refractive index structures, representative of turbulence, and LIDAR to measure horizontal winds through the boundary layer at

extremely high spatial resolution. These instrumentations were a significant part of the CASES-99 study and analyses of data taken there will continue at a high level of funding. New opportunities to measure and characterize wind fields in urban settings will be sought. Additional measurement technology for temperature and/or water vapor or tracer concentrations is of great interest.

TERRESTRIAL SCIENCES PROGRAM

A. General Information

Army Terrestrial Sciences basic research addresses the broad spectrum of terrain and land-based phenomena that affect the Army, from home station to its deployment and sustainment in the field. It is concerned with the impact of the surface, near-surface, and subsurface environment on Army activities and is directed at those particular elements that have the most significant bearing on the full spectrum of Army operations. Of priority interest is the investment in basic research to address science challenges relevant to critical capability gaps identified for the Army *Future Force*. Additional issues of particular importance are improved approaches to landmine, IED, and UXO detection plus the management and stewardship of Army installations, particularly the sustainability of Army training and testing lands and the remediation of Army contaminated sites.

Because the natural environment is, by nature, a highly complex and dynamic system characterized by complicated feedbacks, there is an increasing need for multidisciplinary approaches to address the multifaceted problems that are addressed by the ARO Terrestrial Sciences basic research program. This extramural research program is developed in conjunction with the laboratories of the USACE Engineer Research and Development Center and the Countermine Division of the US Army CERDC Night Vision and Electronic Sensors Directorate. It is also coordinated with related programs in other Department of Defense and Federal agencies. The core funding of the Terrestrial Sciences Program comes from the Army. Other funding sources, both within and outside the Army, are aggressively pursued. Together, this coordination and leveraging in areas of common interest brings more Terrestrial Sciences knowledge to the Army than would otherwise be the case.

B. Thrusts and Trends/Workpackages

Terrain affects all aspects of military operations. The effective understanding and use of terrain is critical to military success on the battlefield. It is in effect a force multiplier, affecting mission planning, system performance, unit mobility and effectiveness, and training readiness. At present, the Army cannot rapidly and efficiently perform the terrain analysis that is required before vehicles and weapons can be deployed. A capability to remotely sense and interpret the features of and upon the earth's surface, and an automated capability/methodology for handling and analysis of large aggregates of remotely sensed data are critical for the 21st Century Army. Terrain data consists of information about land surface elevation (i.e., topography), ground character information,

natural terrestrial features and attributes, man-made targets, and both natural and urban environments.

Research in *Terrain Properties and Characterization* is aimed at the effective understanding and use of terrain for soldier and system success. Accurate assessment and characterization of terrain data in near real-time is a high-priority research issue. Research related to terrain properties characterization is directed toward two general issues: (i) fostering the development of advanced geoscience capabilities for the rapid post-acquisition generation, analysis, and utilization of terrain information acquired through remote sensing approaches; and (ii) the enhancement of current geophysical and geochemical sensing techniques of interest to the Army and the development of new sensor technologies, particularly that to address the high priority problem of landmine, IED, and UXO detection. Understanding the physical character of the top half-meter of soil at both the micro- (c. 5 cm) and macro- (c. 10 m) scale is essential for the detection, identification, and neutralization of IEDs, landmines, and UXO. A fundamental understanding of the micro-scale is needed for the development of new, and the optimization of current, sensor technologies and signal processing algorithms. An ability to estimate macro-scale soil characteristics over larger areas worldwide is needed to guide the operational deployment and optimization of mine detection and neutralization assets. Currently, such soil character knowledge and capability to estimate the required soil physical properties over large spatial areas in real-time do not exist.

Research in *Terrestrial Processes and Dynamics* is oriented towards the development of an improved understanding of surficial processes within the different and varied terrestrial environments that can affect Army operations. Such processes typically are complex and difficult to quantify because they frequently are governed by the nonlinear dynamics that are an intrinsic feature of physical (and biologic) processes. The interaction of Earth surface processes with the ambient landscape operate over a wide range of often-discontinuous time and space scales. Explicit consideration of these processes and their interactions will lead to critically-needed improvements in the ability to predict both the effects of the ambient environment on Army operations and the impact of Army activities on the natural environment. The primary objectives of efforts to characterize the natural environment and understand terrestrial processes are to better prepare the soldier for combat and to contribute to the next generation of battlefield and land management decision aids. An important application of this research is to develop or enhance integrated system models and simulators.

Research in the area of *Terrestrial System Analysis and Modeling* is aimed towards enhancing current Army modeling capabilities of the surface and near-surface environment. These efforts typically are directed toward mobility analysis, watershed response, groundwater flow and transport, the prediction of winter specific engineering effects military reservation, and land response to military testing and training activities.

C. Research Investment

The FY04 allocation of Army basic research funds for the Terrestrial Sciences core program was just under $1M. An additional $3.0M was received from a variety of Department of Defense (DoD) and Army sources including the DoD University Research Initiative program (MURI), Defense Experimental Program to Stimulate Competitive Research (DEPSCoR), and Defense University Research Instrumentation Program (DURIP), DoD Presidential Young Investigator Program, Army Historically Black Colleges and Universities/Minority Institutions (HBCU/MI) initiatives, the Army Small Business Innovative Research and the Small Business Technology Transfer Programs, the Army Corps of Engineers, and US Army Yuma Proving Ground. Finally, $6.5M was received through two Congressional set-asides.

D. Principal Investigator Interactions

Since 1998, researchers from Duke University (L. Carin and L. Collins), Georgia Institute of Technology (W. Scott), and the University of Mississippi (J. Sabatier) have been collaborating with the Countermine Program of the CECOM Night Vision and Electronic Sensors Directorate in the development of new and improved technical approaches, sensor models, and signal processing algorithms for both handheld landmine detection and developing standoff detection technologies. Significant technology transfer has occurred from this focused research over the past year. Other Terrestrial Sciences program Principal Investigators have had strong interactions with one or more of the COE-ERDC laboratories during the course of their projects. For example, V. Petrenko and I. Baker of Dartmouth College have been working closely with the Cold Regions Research and Engineering Laboratory in different aspects of their ice physics and micromechanics research programs. F. Ogden of the University of Connecticut, E. Mesehle of the University of Louisiana, and S. Wang at the University of Mississippi have close ties with the surface hydrology program at the Coastal and Hydraulics Laboratory. A. Tordesillas of the University of Melbourne in Australia is collaborating with J. Peters of the USACE –ERDC Geotechnical and Structures Laboratory to develop a micromechanical constitutive model of granular media that captures the key aspects of granular media behavior under dynamic loading. S. Upadhaya of the University of California at Davis is undertaking fundamental geotechnical engineering research in conjunction with the USACE–ERDC Geotechnical and Structures Laboratory to generate a new capability for the *in-situ* determination of fundamental soil engineering properties necessary to predict vehicle mobility and traction. E. McDonald and colleagues at the Desert Research Institute are studying the intrinsic nature of dust from Iraq, including its physical character and chemical composition, in partnership with scientists and engineers from the U.S. Military Academy, the USACE–ERDC Geotechnical and Structures Laboratory, and Yuma Proving Ground to determine if a particular aspect of the fine-grained soil and dust material is the cause of weapon (M16A2 rifle) malfunction presently occurring in Iraq. Several researchers have conducted field research for their ARO basic research projects at Army installations: P. Bierman (U. Vermont); E. McDonald (Desert Research Institute), J. Hendrickx (New Mexico Tech), and E. Wohl at Yuma Proving Ground, AZ; X. Hu (Desert Research Institute) at Sierra Army Depot, CA;

B. Minsker (U Illinois) at Umatilla Army Depot, OR; J. Hendrickx (New Mexico Tech) at Schofield Barracks, HI; G. Tucker (U. Colorado) and R. Bras (MIT) at Ft. Carson, CO; E. McDonald (Desert Research Institute) and J. Heaton (Redlands U) at Ft Irwin, CA; and M. Cablk (Desert Research Institute) at USMC Air Ground Combat Center at Twentynine Palms, CA.

III. SPECIAL PROGRAMS

A. Multidisciplinary University Research Initiative (MURI) Centers

Two block-funded research grants was awarded in late FY02 as part of the DoD MURI program to address the general problem of detection and classification algorithms for multi-modal inverse problems. The first grant is a Duke University-led effort on 'Multi-Modal Inverse Scattering for Detection and Classification of General Concealed Targets: Landmines, Targets under Trees, and Underground Facilities' consisting of a research team from Duke University, Georgia Institute of Technology, and Stanford University. The second grant is a University of Michigan effort on 'Sequential, Adaptive Multi-Modality Target Detection and Classification Using Physics-Based Models.' This MURI program began in September 2002 to undertake the multidisciplinary research necessary to develop new approaches for exploiting multiple sensor modalities in DoD-relevant inverse problems. The research addresses the general problem of detection and classification of targets surrounded by dielectric layers and stochastically distributed scattering centers. In this context, the inverse problem is one of inferring target and environmental; characteristics using data from multiple sensors. The focus of the program is on three detection/classification applications: landmines, targets obscured by foliage, and underground facilities. To ensure the methodology developed is fundamental and offers cross-cutting application impact, the research teams have been encouraged to demonstrate the applicability of their approaches to more than one of the three focus problems.

Both MURI projects are addressing the general problem of detection and classification of targets surrounded by dielectric layers and stochastically distributed scattering centers. The research seeks to address two classes of inverse scattering algorithms: those that are directly physics-based (i.e., involving direct use of the associated underlying wave equations) and those that are statistically physics-based (i.e., which use forward algorithms and available measured data for training statistical models). Algorithm and sensor adaptivity play a central role in this research, with phenomenological links across multiple sensors utilized from one modality to constrain and regularize the inversion data from another. The Duke-led program is underpinned by an innovative and coordinated education program that, over the first two years, has featured graduate students doing summer work at the CECOM Night Vision and Electronic Sensors Directorate Countermine Division and annual research workshops at Stanford University and the University of Minnesota related to specific aspects of the MURI research. The Duke-Georgia Tech-Stanford collaborative effort reported ore than 30 significant research accomplishments plus 82 abstracts, conference proceedings volume contributions, and

journal papers published or pending publication during the first 24 months of the MURI program. Foremost among the research achievements was the development of forward models to enhance understanding of multi-modal sensor physics, for transfer to improved inversion algorithms, development of coarse-to-fine data-analysis techniques that prioritize those data likely to be most important for the inversion task, exploitation of the clutter inherent to most inversion problems, through development of time-reversal technology that yields improved image resolution, implementation of controlled multi-sensor measurements, such that multi-sensor data is carefully geo-referenced, development of new physics-based nonlinear inversion algorithms that explicitly incorporate multi-modality wave equations, design of Bayesian inversion algorithms that take a statistical perspective, and employ labeled and unlabeled data for design – with priors based on the underlying physics, and design of sensor-management techniques to optimize the multi-modality inversion, employing techniques from the optimal design of experiments. The smaller Michigan MURI effort had 12 major research accomplishments and 48 abstracts, conference proceedings volume contributions, and journal papers published or pending publication during the first 24 months of the MURI program.
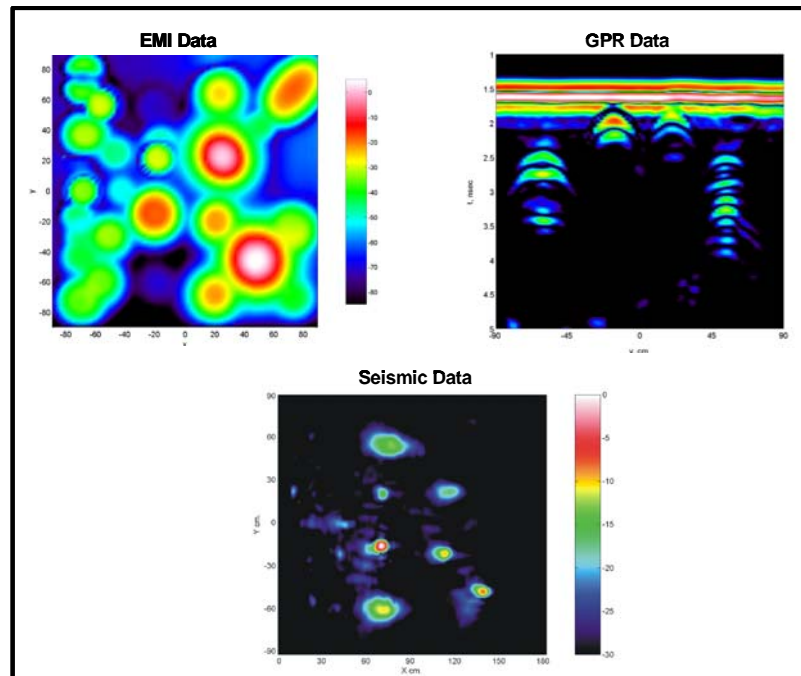
Figure 1. Measured 3-sensor data for buried mines in the presence of clutter. This data is processed using adaptive multi-modality

B. Historically Black Colleges and Universities/Minority Institutions (HBCU/MI)

Using Geographic Information Systems to Assess Fracture Zone Development at Multiple Scales
Dr. M. Gross, Florida International University

The primary focus of this project is the use of a combination of Geographic Information System (GIS) spatial analysis, structural field mapping and numerical modeling techniques to document the development, occurrence and hydrologic significance of through going fracture zones in layered rocks. GIS techniques is being used to analyze fracture populations at different scales in an effort to identify conductive fracture zones in the subsurface, evaluate the heterogeneity of fracture systems, and establish scaling relations of fracture attributes. Outcrop fracture zones have been measured and analyzed to quantify their physical characteristics and to understand the mechanisms of fracture zone development. Once established, fracture zone architecture is incorporated into discrete fracture network models to simulate flow through fractured media. This project is merging the process-oriented approach of structural geology with powerful quantitative tools of GIS-based spatial analysis. The results of this innovative research is providing the research community with a better understanding of the origin and character of through going fracture zones and their contribution to subsurface fluid flow.
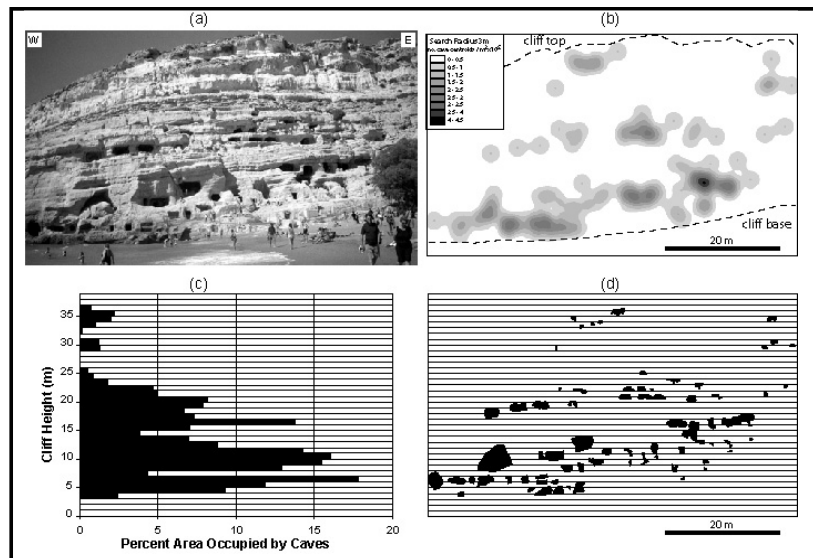
Figure 2. Results of geospatial analysis of caves exposed along the cliffs of Matala, Crete. (a) Photograph of caves; (b) Cave density map; (c) Profile of cave area distribution; (d) Sketch of caves. Note linear trends of high cave density in (b) and major peaks in cave area in (c) that identify specific horizons of enhanced cave development. These horizons can be mapped and selected for closer scrutiny by ground forces

C. Small Business Innovation Research (SBIR)

Simultaneous Measurement of Tracer Concentrations and Winds

A Phase II SBIR contract in Atmospheric Sciences awarded to Coherent Technologies, Inc. (CTI) of Lafayette, Colorado develops capability to measure propylene tracer gas concentrations using differential absorption LIDAR (DIAL) techniques with the MAG-1 LIDAR system they previously developed. A unique technique for measuring the propylene signals in the mid IR region using more sensitive existing devices in the near IR was a crucial factor in sensitivity studies. An additional ability to measure aerosol backscatter at three wavelengths can provide information for aerosol size distributions. The new system will measure tracer (propylene) concentrations at high time and space resolution for comparisons with *in situ* tracer measurements of aerosol size distributions, and simultaneously measure the winds affecting the plume dispersion aloft as well as near the ground. Field testing of the system has been delayed as no tracer programs were executed at the Dugway Proving Grounds using their propylene tracer system

Further Development of 3-D In-Situ Soil Stress Sensor

Dynasen, Inc. of Goleta, California continued work on the development of sensor system for *in-situ* 3-D soil stress analysis in soils resulting from vehicle-terrain interaction for application to vehicle-terrain interaction modeling and simulation under a SBIR program Phase I award. The system consists of a compact and ruggedized stress sensing unit and field-portable control and data acquisition system. The 1 cubic centimeter sensor unit will consist of three solid- or liquid-coupled, high-output thin-film piezoresistive carbon stress gauges mounted in an orthogonal pattern on the faces of a solid substrate or behind its faces in small fluid cavities that will have the capability of resolving stresses as low as a few PSI up to stresses as large as 15,000 PSI in dynamic or static environments. Dynasen was selected for a Phase II award to complete the development of this new technology.

Software Driven Virtual Minefield

Engineering Technology Inc. of Orlando, FL received a Phase I SBIR award and has been selected for Phase II for the research and development work that is necessary for the creation of a new training capability for landmine detection. The 'Software-Driven Virtual Minelane' training system uses real-time video tracking technology (the sweep monitoring system) and realistic audio-visual feedback to a trainee operator for performance enhancement. When an operator uses the virtual minefield system, the detector simulator generates a realistic audio response as if it was a true working detector system operating in an environment with real buried mines. The system can also support operator training and re-orientation in new environments and experimentation with variable operator cuing formats. The Phase II goal is to provide the operator of a combined EM detector-GPR handheld landmine detection system a virtual experience for training that combines a virtual minefield with realistic sensor signals corresponding to

actual target signatures encountered in the field under various realistic soil and environmental conditions.
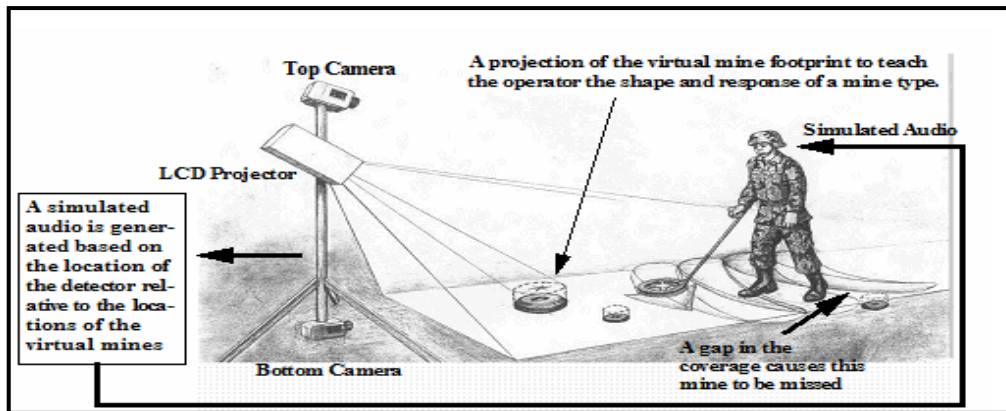
Figure 3. Concept drawing of the 'Software-Driven Virtual Minelane' training system.

D. Defense Program to Stimulate Competitive Research (DEPSCoR)

Seven research grants were active under the Defense Program to Stimulate Competitive Research (DEPSCoR) program during FY04, which addressed environmental sciences research requirements. Following are brief summaries of a selection of these projects.

Atmospheric Boundary Layer Structure and Dynamics Revealed through Adaptive Imaging Techniques
Dr. R. Palmer, University of Nebraska

The Turbulent Eddy Profiler uses a 90-element phased array receiving antenna to measure scattering from refractive index structures in the atmospheric boundary layer. Field studies using alternative array layouts have been conducted and show significant improvement in the analyses of wind fields and their four dimensional evolution.

Investigation and Simulation of Streambank Erosion Processes in the Upper Jordan River, Utah
Dr. G. Duan, Desert Research Institute

The objective of this hydraulics project, in its final year, is to undertake the research necessary to enhance the 2-D, depth-averaged *ENCHH2D* channel hydraulics model through the addition of more physically realistic physical processes. Specific tasks being undertaken include: testing the hypothesis that the rate of basal erosion in natural rivers is determined by the gradient of longitudinal sediment flux and the strength of secondary flow, identifying the mechanisms and critical conditions for bank failure, develop a non-uniform and non-equilibrium sediment transport model, developing a model bank failure processes, and calibrating and verifying the flow sediment transport, and bank erosion

modules of the enhanced predictive model. The second phase will undertake a field validation study on the Upper Jordan River in Utah for the COE Sacramento District that will demonstrate the model's potential as a useful hydrologic decision aid.

Land Mine Detection: Dealing with Spatial and Temporal Soil Variability
Professor J. Hendrickx, New Mexico Institute of Technology

This second-year project is aimed at determining quantitatively the effects of soil variability at different spatial and temporal scales in different sensor-soil-landmine systems through field observations, laboratory measurements, and computer modeling. Five specific research tasks will be undertaken: (i) further development and field testing of the GPR model that was previously developed for the prediction of radar signatures of metallic, non-metallic, and low-metal mines under field soil conditions that exhibit spatial and temporal variability; (ii) further development and field testing of the *IR-HYDRUS2D* model for the prediction of thermal signatures of metallic, non-metallic, and low-metal mines under field soil conditions that exhibit spatial and temporal variability; (iii) measurement of the dielectric properties of field soils to determine their natural variability; (iv) field testing of GPR and IR mine detection sensors under tropical conditions, and (v) field testing of GPR and IR mine detection sensors in the beach environment. During the year, Professor Hendrickx cooperated with the Yuma Proving Ground Tropic Regions Test Center to undertake land mine detection environmental phenomenology research at Schofield Barracks, Hawaii and in Panama.

Pavement Material Characterization and Modeling of Long-Term Airfield Pavement Performance
Professor R. Siddharthan, University of Nevada - Reno

The objective of this research was to develop a comprehensive empirical-mechanistic approach that consists of field calibration and state-of-the-art analytical procedures to predict pavement response. The first phase of the project developed a finite-layer based analytical model, *3D-MOVE*, to study the dynamic response of pavement under complex 3-D stress distributions. The second phase of the project focused on the calibration and validation of the analytical method at three field tests (Penn State University, Minnesota, and South Dakota Road Tests). The new approach can be used to study the responses generated by atypical vehicular loading under variety of field conditions. For example, loading from new aircrafts such as Boeing-777 and MD C-17 landing gears under taxiing and turning. A user-friendly interface has also been developed so that the *3D-MOVE* software can be easily used in a PC under Windows environment. Both windows and DOS versions of the software was transitioned to the USACE-ERDC Geotechnical and Structures Laboratory during the final stage of the project.

Quantifying Erosion and Sedimentation in Extreme Environments: Refining and Applying the Cosmogenic Method for Army-Relevant Landscape Analysis
Dr. P. Bierman, University of Vermont

The specific objective of the research proposed is twofold: (i) to use cosmogenic isotopes such as Be^{10} and Al^{26} that accumulate in sediment to better understand in a fundamental way the rate at which landscapes change and evolve through time and space, and (ii) to refine laboratory and analytical methodologies so that a broader range of landscapes can be studied, particularly those in extreme environments where erosion and sediment transport may be extremely rapid. Fieldwork will be undertaken at several Army installations in the arid western US (e.g. Ft. Irwin National Training Center, CA; Yuma Proving Ground, AZ; Ft. Carson, CO; and Yakima Training Center, CA), in a tropical location (Chagres River basin in Panama), in a cold-climate permafrost location (Ft. Wainwright, AK), and at one or more humid/temperate eastern US locations yet to be determined. This work will be directed toward sampling sediments from hill slopes and river channel networks in order to undertake a determination of the cosmogenic nuclides Be^{10} and Al^{26} in order to understand at what rate sediment is generated from different parts of a particular landscape and how that sediment is routed through the stream/river channel network to eventually come to rest in reservoirs.

Reactive Chemical Transport in Natural Media: Heterogeneoty, Nonstationarity, and Uncertainty
Dr. X. Hu, Desert Research Institute

This project is utilizing a three-step geostatistical method that provides a way to combine non-linear terms into constitutive theory, to construct a 3-D hydraulic conductivity distribution for a TNT-contaminated area within the Sierra Army Depot, CA. A novel eulerian approach that simulates conservative transport in the saturated zone is being extended to reactive chemical transport and then used to study the role of physical and chemical heterogeneity and anisotropy on the contaminant dispersion process.

Understanding Clutter and Texture in Parametric Radar Imagery of Terrestrial Targets
Dr. J. Henson, University of Nevada – Reno

The objective of this project, now in its last year, is to improve fundamental understanding of radar texture through the development of techniques for the analysis and high-speed synthesis of radar imagery for naturally-occurring distributed targets as a function of radar system operating parameters, including frequency, resolution, depression angle, altitude, detector type imaging mode, and dynamic range. The final year's effort involves the characterization and understanding of radar clutter data associated with naturally occurring terrain types in synthetic aperture radar (SAR) imagery. The objectives are to develop signal simulation and signal processing techniques to investigate the effects of radar system parameters and terrain scattering center regimes on the underlying image data probability distributions, develop automatic image segmentation techniques and software capable of successfully segmenting

MSTAR imagery, and to study Gray Level Co-Occurrence Matrix (GLCM) techniques for the classification of naturally occurring terrain types in the MSTAR data set, and integrate automatic segmentation and GLCM techniques to provide Automatic Terrain Recognition software tools.

Figure 4. MSTAR and SARTAC simulated images
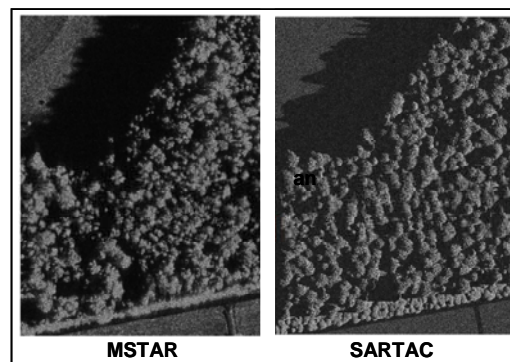
E. Defense University Research Instrumentation Program (DURIP) and Historically Black College and University/Minority Institution (HBCU/MI) Research Instrumentation Program

Two grants in the Terrestrial Sciences were awarded in FY04 as part of the Defense University Research Instrumentation Program to provide research instrumentation enhancement at universities engaged in the Army's environmental research program and one grant was awarded under the Historically Black College and University/Minority Institution (HBCU/MI) Research Instrumentation Program for research infrastructure enhancement. F. Ogden at the University of Connecticut received hydrometeorological instrumentation for 'Measurement of Evapotranspiration, Interception, and Runoff Production in the Seasonal Tropics, Panama' and A. Garcia at University of Puerto Rico – Arecibo received general laboratory instrumentation for 'Implementing Environmental Sciences and Engineering Laboratory'.

IV. SCIENTIFIC ACCOMPLISHMENTS

JointUrban 2003

Although conducted in July 2003, JointUrban 2003 (JU03) atmospheric dispersion study was conducted in Oklahoma City, Oklahoma continues to produce heretofore descriptions of the atmospheric boundary layer as the airflow transitions the enhanced roughness of cluster of tall buildings in a downtown center. This study advanced community knowledge about movement of contaminants in and around cities and into and within building interiors. The resulting data continues to be used to improve, refine

and verify computer models that simulate the atmospheric transport of contaminants in urban areas.

Doppler Lidar Measurements of Wind, Turbulence, and Aerosol Backscatter
Dr. Ronald Calhoun, Arizona State University

Two key objectives of this effort are: (a) to improve our understanding of the physics of atmospheric flows in urban areas, and (b) to obtain data that can be used to test and improve numerical models of flow and dispersion in the urban atmosphere. The ASU Doppler lidar was deployed to participate in the JU03 to obtain data to advance both of the goals. First, lidar data can provide more complete outer boundary conditions for high resolution models. Secondly, lidar data can provide information on urban-scale and intra-urban winds. Of particular interest were the effects of urban morphology on the distortion of the flow as it encountered and traversed the built-up area of the central business district (CBD) and the restructuring of flow further downwind. These efforts, in conjunction with a similar lidar system operated by the Army Research Laboratory, were in primary support of the intensive operating periods (IOP) during daytime or nighttime releases of tracer material. Thirdly, the ASU lidar was used to provide information on atmospheric turbulence along lines-of-sight and in horizontal layers from elevation scans and examine boundary layer processes like gust fronts, wind shear as opportunities arose.

Dr. Calhoun's lidar participated in JU03 from a location approximately 3.8 km SSE of the CBD. Usual scans consisted of measurements of the wind profile through the boundary layer using the VAD technique, followed by an azimuthal raster scan across the CBD face and 10 degrees to either side in 0.5 degree increments followed by a 0.5 deg elevation angle change. The scans took approximately 2 minutes and were repeated for about 25 minutes. Lidar range resolutions were set to 50 m and scanning gives ~ 40 m azimuthal and height resolution at the range of the CBD.

Numerous experiments were performed, for example, (a) Staring studies toward the CBD, (b) 4DVAR data acquisition [volume scans coordinated with the ARL Lidar Team], (c) PPI sweeps during severe storm activity [which unfortunately partially dissipated as it approached OKC overnight], (d) Staring over the PNNL profiler site, (e) co-planar coordinated PPI scans with ARL , (f) coordinated, intersecting RHI scans with ARL, and (g) a plume tracking experiment during the evening of July 4 Approximately 120 Gigabytes of spectral and product data for IOP's and the days/nights between IOP's have been stored on 33 DVD's. As the campaign was completed in early August, a significant amount of data quality control, operational analyses, research analyses, and intercomparisons with other data sources are beginning. Figures 5 and 6 are representative of some analyses.

Building Wake Observations

On several occasions, the ASU Lidar performed RHI scans that intersected the buildings of the CBD. These scans clearly show a velocity disturbance above the buildings and may provide some data about the effect of the urban roughness on the Boundary Layer

height and structure. Figure 5 shows one of these RHI scans. The change in velocity above the buildings at a range of 3.8 km shows a strong acceleration in the 200 m above the city as a result of the winds encountering the blunt front of the CBD. Also the scan shows stronger, but more intermittent winds below 500 m than the relatively stratified flow aloft. So far, models have not captured this feature.
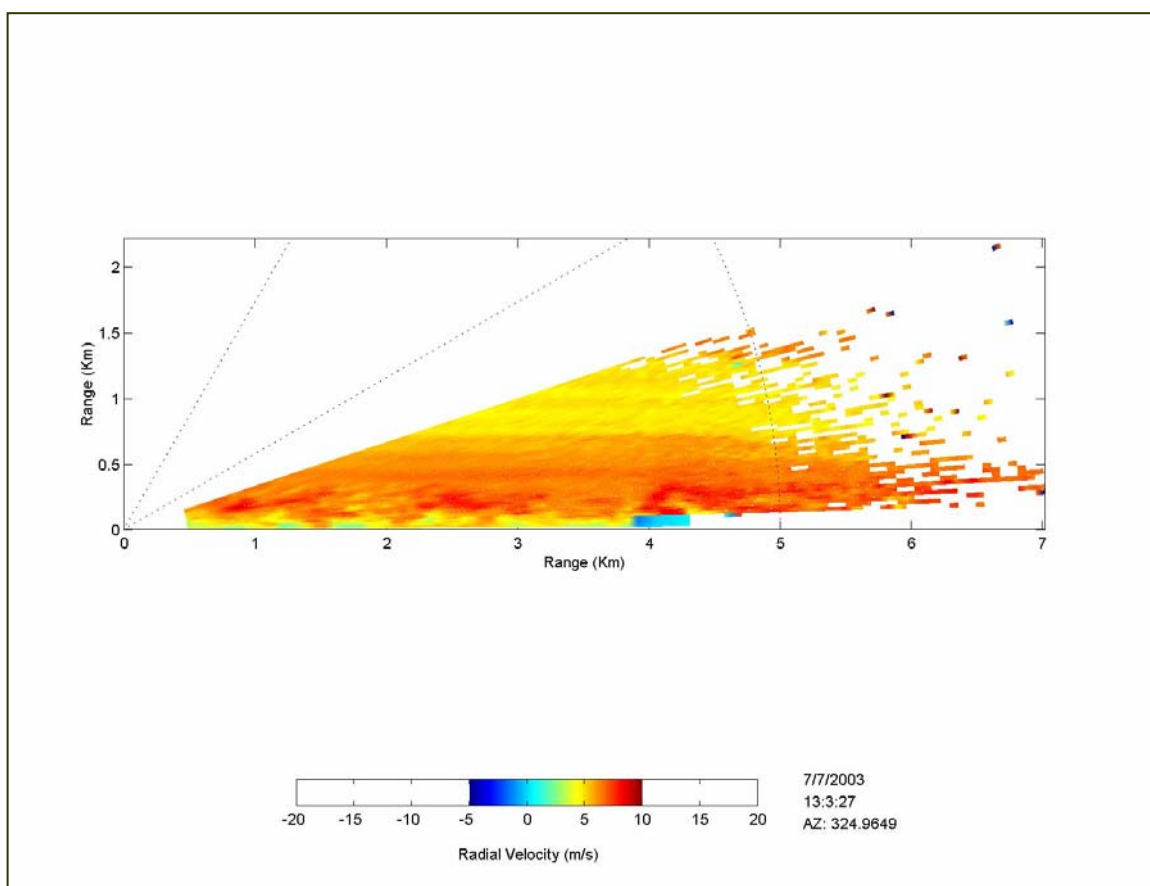
Figure 5. RHI scan of winds encountering the CBD.

Wind and Turbulence in the Urban Flows

On occasions, the lidar stared at one part of the CBD as shown in the red dot of Figure 6. The mean wind speed in each range gate from the lidar to about 6.5 km down range was computed. The rms of the values of wind – indicative of the turbulence - in each range gate was also calculated. As shown in the figure, wind speed showed a significant reduction just before reaching the CBD with a rise in turbulence intensity as the prevailing southerly wind begins to "feel" the obstructions of the CBD. Over the CBD mean wind speeds increase, but are less smoothly varying while turbulence intensity increases monotonically to the lidar range.
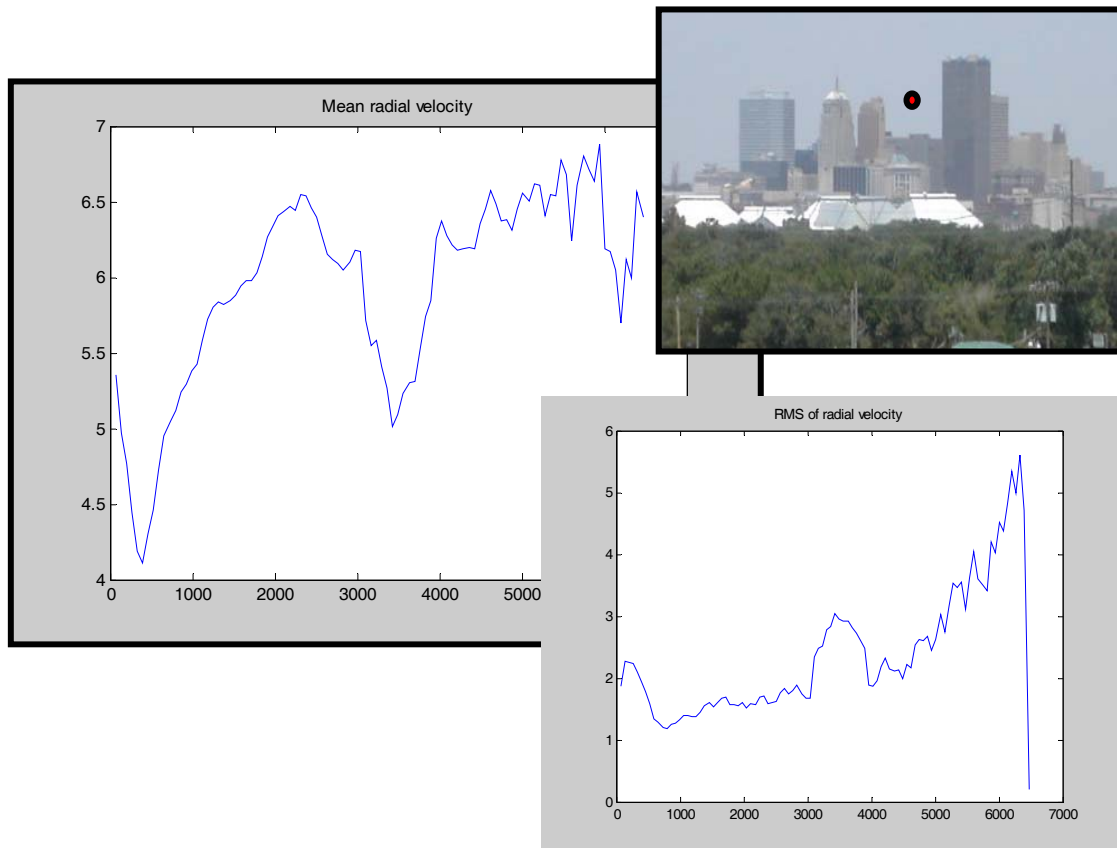
Figure 6. Mean radial wind speed and rms velocity fluctuation in airflow entering and transecting the Oklahoma City central business district.

Turning and outflow studies

In the large majority of cases, the prevailing winds were from the SSE through SW and the urban wake was not readily discernable from the ASU location. On a few occasions, the mean flow direction turned dramatically and rapidly until the wind approached from the north. These periods are most likely tied to thunderstorm conditions that existed during the times the scans were being executed. During these flow reversal periods,

wake region characterized by a radial velocity deficit can be clearly seen by the ASU Lidar. Animations of observation of these wake regions reveals the feature meandering over approximately 10°-15° and a clearly observable feature at times up to 1km downwind of the buildings. Figure 7 shows these features.

Figure 7 – Urban Wake region (Note the length of the observed feature). Box shows CBD area.
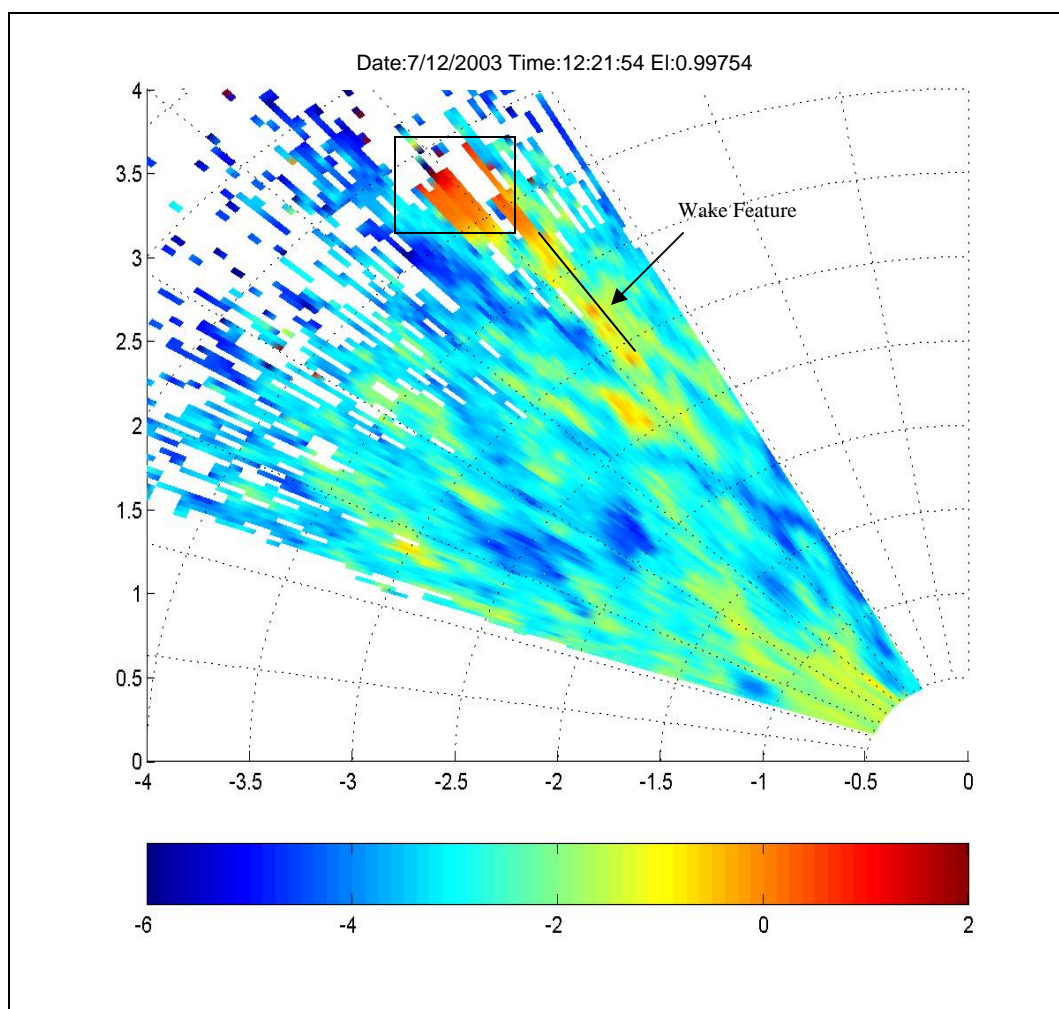
CASES-99

The 1999 Cooperative Atmospheric Surface-Exchange Study (CASES-99) was motivated by the search for solutions to vexing scientific problems in stable and/or nocturnal atmospheric conditions. A well-coordinated plan of study involving concentrated observational efforts was needed to develop the acumen required to devise new paradigms for parameterization of the very stable NBL and surface layer.

One of the four science goals of the research program was to investigate the structure and evolution of the nighttime boundary layer at the ground and aloft.

Studies of high resolution turbulence, stratification, and instabilities in the nighttime boundary layer
Dr. Ben Balsley, University of Colorado, Cooperative Institute in Environmental Sciences

A Tethered Lift System developed at the University of Colorado Cooperative Institute in Environmental Sciences by Dr Balsley, was deployed during the CASES-99 study. This unique system features an instrument package to measure temperature, wind speed and humidity at 200Hz, enabling measurements of ε, the rate of decay of turbulent kinetic energy, and C_T^2, the temperature structure function constant. Three to five of these packages are suspended below a tethered balloon which can be carefully moved up or down at a low speed. This permits several duplicate instrument passages through the same atmosphere at a controlled rate. Because of their fast response, the instruments have identify extremely significant gradients in the measured variables, especially C_T^2 and ε. On occasions, thin layers of very thin layers will exhibit a factor of 100 or more increase or decrease from the prevailing value in these quantities. Such layers can be recognized in C-Band radars and in sodars and thus are significant in nocturnal boundary layer propagation. The research team terms them "bite-outs." A few examples of preliminary analyses that support the apparent ubiquity of these sharp gradients defining the top of the nighttime stable boundary layer and the residual layer bite-outs.

First, in Figure 8, an 8-sec-averaged vertical profiles of wind speed, temperature, C_T^2, and ε between 0-400 meters is shown. These data were obtained one night during CASES-99, and show a very low Low-Level Jet (LLJ) maximum. The temperature profile also changes from very stable (0-55m) to almost isothermal above that height. The height of the nighttime stable boundary lies between 0–55m, with the entire height range shown above that defined as the residual layer. In this example, a clear bite-out: in both turbulence profiles can be seen between 55-170m (indicated by the double-ended arrow). Additional possible bite-outs in the energy dissipation profile are also visible around 270m and 320m (single-ended arrows).

A similar bite-out region between roughly 150 m and 240 m, obtained on a different night of observations during CASES-99, is shown in figure 9. The magnitude of the turbulence decease near 150 m is almost three orders of magnitude. In this case, there is a clear similarity in both the C_T^2 and ε profiles below about 230 m. Even though these profiles represent 20-second averaged profiles (~8 m vertical height resolution), the level of the bottom gradient appears to change by a factor of 300 in only a few meters. In this instance the upper level of the bite-out region is more obvious in C_T^2 than in ε.

The evolution of the steep profile shown in Figure 9 over about six hours is shown in figure 10. Here individual (averaged) profiles have been offset for ease in viewing, with the earliest profile appearing on the left. Each profile is marked with the time over which

it was taken. The rapid decrease in C_T^2 suggests the top of the surface-based boundary layer. The subsidence of that top over the nighttime is clear. Also, the solid circles indicate the height of the maximum wind speed of the nocturnal jet, suggesting that the peak velocity lies slightly above the region of the steep turbulence gradient. There appears to be a close correlation between these two quantities, and other studies confirm this association.

The importance of the role of these structures in the boundary layer is under investigation. Studies are showing that the warm vortex core of the King Air airplane making measurements over the field site can be identified as it drifts in the wind through the TLS arrays. Also the effects of a small surface gully developing atmospheric gravity waves several hundred meters aloft have been identified. With the use of this system, scientists are finding heretofore unknown structures and processes in the nocturnal boundary layer
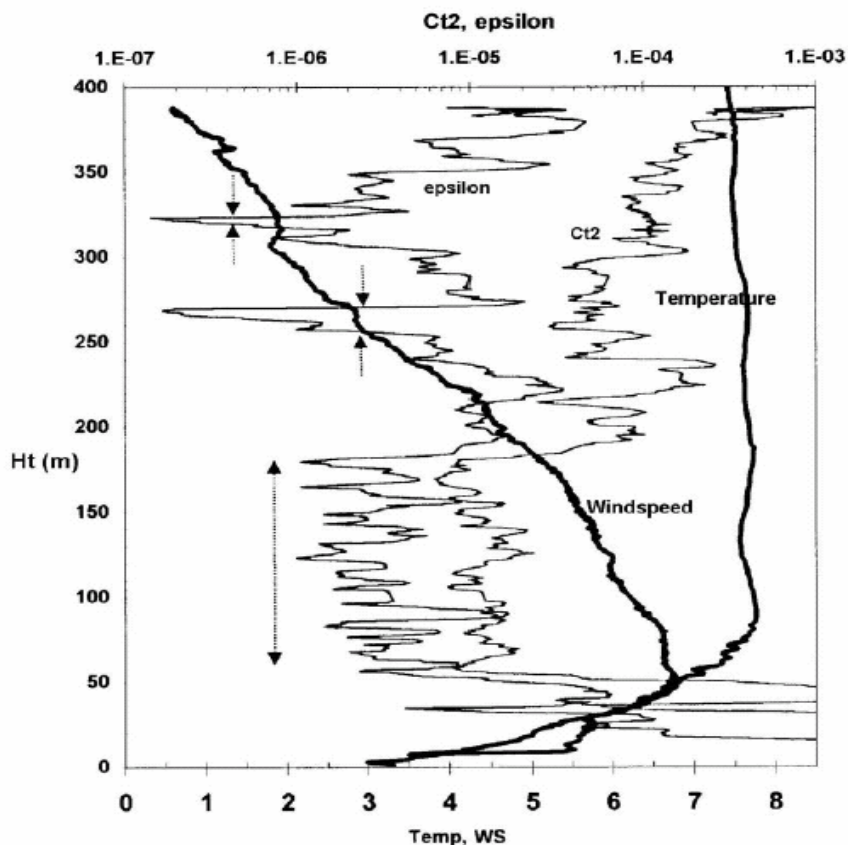
Figure 8. A composite plot of four variables (wind speed, temperature, $C_T 2$, and ε) showing (1)the steep turbulence gradient that exists just above the wind maximum, (2) a turbulence bite-out between that height and about 180m, and (3) smaller bite-out near 270m and 320m. All of these bite-outs are indicated by vertical arrows.
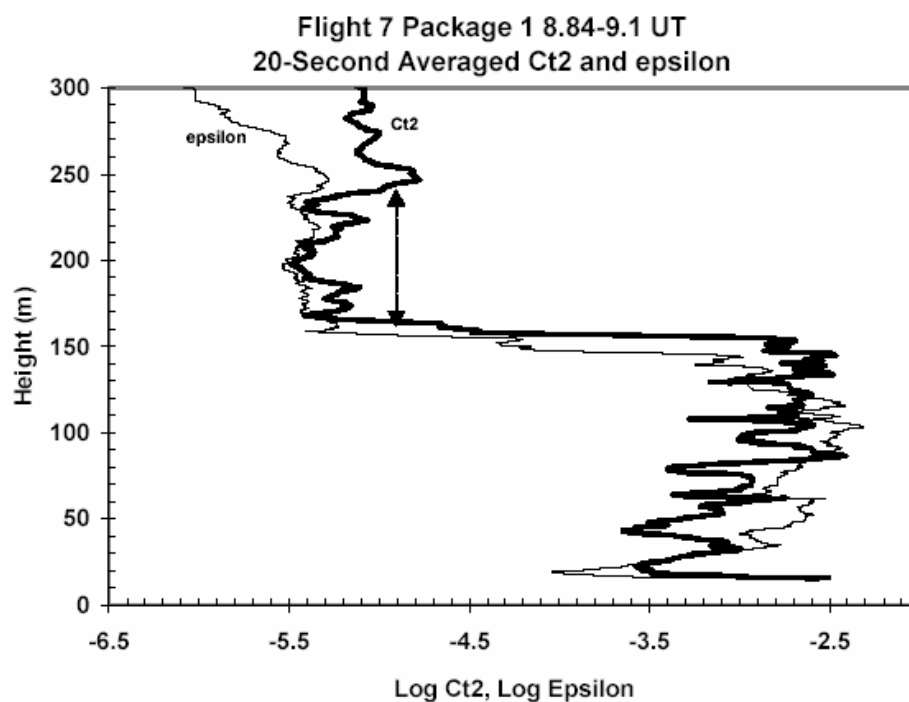
Figure 9. Another steep turbulence boundary on another night during CASES-99. Note the turbulence level drop of almost three orders of magnitude over a very few meters of altitude.
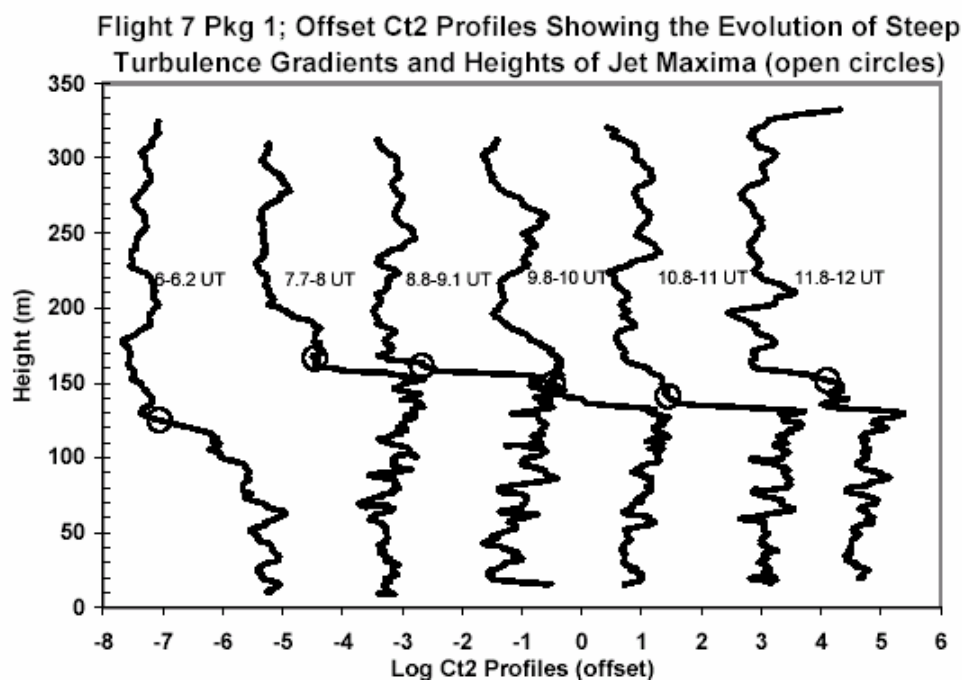
Figure 10. Six profiles of averaged C_T^2 depicting the evolution of the steep gradient in C_T^2 over a six-hour period. The open circle included on each profiles indicate the height of the peak wind velocity.
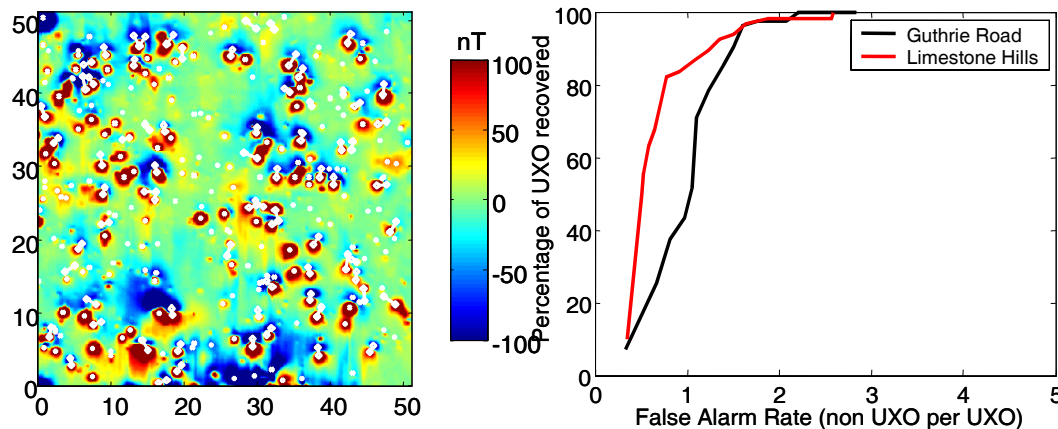
Figure 11. (a) Automated detection of anomalies using a wavelet transform approach; (b) Advanced discrimination resulting in very low false-alarm rate with 100% recovery of detected UXO.

Locating and Characterizing UXO's Using Time Domain Electromagnetic Induction
Professor D. Oldenburg, University of British Columbia (Canada)

The broad objective of this project is to develop and test a method of interpreting a new form of geophysical site characterization information, namely time-domain electromagnetic induction data that has the potential to discriminate between UXO and non-ordnance objects. Techniques have been developed for discrimination with either magnetics or TEM alone, and for both datasets considered jointly. The magnetic analysis begins by first finding a best fit dipole for the observed magnetic data. Anomalies are then prioritized in a dig list by using the field evidence that UXO tend not to be remnantly magnetized. Existence of magnetic type curves from known ordnance items aid in identification and prioritization. Time domain EM data are inverted under the assumption that the measured fields can be represented by a two-dipole model. Ratios of certain of these parameters are diagnostic as to whether the object is magnetic or not. Ratios of other TEM parameters yield information about shape of the object; in particular, whether the object is rod-like or plate-like.

There is a fundamental non-uniqueness when attempting to extract such shape information from magnetic data alone. However, if a spheroid represents the object and its orientation can be constrained, then the aspect ratio of the object can be found. Inversion of TEM data can be non-robust in the presence of data errors, but the inversion results can be improved if the horizontal and vertical location of the object is restricted. These considerations lead to a co-operative inversion whereby location-information is extracted from inversion of magnetic data. This location-information constrains the TEM inversion from which discrimination parameters are evaluated. In addition, the orientation from the TEM inversion can be included in the spheroidal magnetic analysis to extract shape information and thus aid discrimination. The computing codes needed to perform forward and inverse modeling of magnetic and TEM data, and to make

discrimination decisions, are packaged in *UXOLab*, a Matlab code with a GUI interface. During the year, two COE-ERDC staff members were trained on the use of the *UXOLab* software package.

The Structure and Physical Properties of River and Lake Ice
Professor I. Baker, Dartmouth College

The objective of this project is to gain fundamental knowledge about the physical properties structure, and micromechanical behavior of natural freshwater ice that is needed to provide the foundation for the development of physics-based ice mechanics models. The research, now in its second year, is employing X-ray topography and a low-vacuum SEM/EDS technique utilizing controlled sublimation on a cold stage that was developed under previous ARO grants to study the microstructure and impurities in natural fresh-water ice from various rivers and lakes and to determine how the impurities and microstructural features in such ice affect mechanical and electrical properties. Ice is being collected yearly during the months of February and March from the same locations on both Lower Baker Pond, Orford, NH and the Connecticut River near Hanover, NH over a 4-year period from 2001-04. Microstructural analysis has revealed that the microstructure and texture of lake ice change both through the thickness of the ice sheet as well as with location in the lake (*i.e.* middle of the lake compared to closer to the shore or near a water inlet). Both the microstructure and texture vary significantly from year to year, presumably depending on the growth conditions and the presence of nucleation stimuli at the time of freezing. In some years, the formation of very long, straight grain boundaries and the non-uniform distribution of impurities make characterization of the mechanical behavior of lake ice quite challenging. While some sections closer to the surface exhibiting largely-grained microstructures with straight grain boundaries fail at stresses three or four times less than the strength of S2 lab ice under similar loading conditions, the bottom sections of lake ice are on average stronger, presumably due to the very tight S1 texture which develops towards to bottom of the ice sheet. In sharp contrast, the microstructure, texture and mechanical behavior of river ice do not seem to be greatly affected by the growth conditions and do not vary greatly from year to year: the strength is comparable to that of lab ice with a similar grain size.

Figure 12. Compression test specimen made from lake ice. (a) Untested. Long and straight grain boundaries are visible in polarized light. (b) Tested under biaxial compression. The ice failed prematurely (3-4 MPa) through cracking and sliding along the inclined grain boundaries.
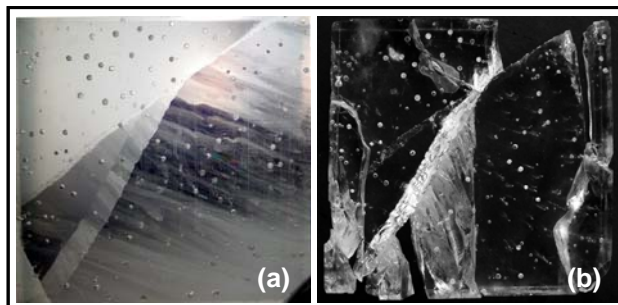
Large-Scale Monitoring and Model Development for Simulating Watersheds with Diverse Runoff Production Mechanisms
Dr. F. Ogden, University of Connecticut

and

Hydrologic Investigations of Low Gradient Watersheds
Dr. E. Meselhe, University of Louisiana

The Army has a pressing need to simulate the soil moisture, and inundated area of watersheds at potentially any location on the globe. Furthermore, the Army Corps of Engineers requires enhanced hydrologic simulation models for land stewardship, sustainable use of reservoirs and training lands. This project seeks improved scientific understanding of the physiographic catchment features that determine runoff response, and the development engineering tools that can convert this understanding into improved predictions in a wide variety of watershed settings. The major aims of this research are to understand the fundamental hydrologic behavior of watersheds that experience both saturation-excess (i.e. Hortonian) and infiltration-excess (i.e. non-Hortonian) runoff production mechanisms at different times of year and under different rainfall regimes (Ogden) and the development of a hydrologic modeling capability for extremely low gradient watersheds that will be used to determine the storage characteristics of such watersheds and their response to large precipitation events (Meselhe).

The major accomplishments of these projects during the past year has been the cooperative effort that has been undertaken with the USCAE-ERDC Military Hydrology Program of the Coastal and Hydraulics Laboratory to enhance the capabilities of the *Gridded Surface/Subsurface Hydrologic Analysis* (*GSSHA*) 3-D distributed hydrological model. The new capabilities being developed for *GSSHA* were focused on implementing detailed descriptions of hydraulics within the distributed hydrologic modeling framework to enhance the predictive abilities of the model. Other accomplishments include: studies regarding the role of subsurface parameters in saturation-excess runoff production, identification and quantification of the hysteretic behavior between wetting and drying cycles at the headwater catchment scale, testing the performance of GSSHA in arid catchment in western Arizona with results demonstrating that the GSSHA approach works well in large arid watersheds, and testing the performance of combined GSSHA/SAC-SMA modeling approach in tropical Rio Chagres watershed of Panama. Results for Panama indicate that the SAC-SMA approach does a reasonably good job of simulating this tropical catchment, but fails to predict the observed anomalously high runoff efficiencies early in the wet season. This result indicates that a new process is involved that is not considered in the model formulation.

Toward Generalized Continuum Models of Granular Soil and Soil-Tire Interaction
Dr. Antoinette Tordesillas, The University of Melbourne, Australia

The project objectives are to: develop micromechanical constitutive models of dry granular materials that potentially could offer a computationally efficient alternative to

DEM simulations and thus fill an important niche in applications beyond the reach of current DEM simulations (*e.g.* soil-structure/machine interaction systems), experimentally validate these constitutive models, and integrate these constitutive models into our contact mechanics model of the soil-tire interaction system. The great majority of existing models of granular media are developed using classical continuum theory, which has the advantage that such models are readily accessible and enjoy widespread use, but have the disadvantage that they possess no length scale with which to accommodate microstructural properties governing bulk behavior of granular media. Thus, the reliability of these models remains questionable. An alternate approach, which is gaining popularity, is the discrete element method (DEM), which deals explicitly with the microstructure and, as such, has the potential to deliver reliable predictions on granular behavior. However, the number of particles in current DEM simulations is limited to a few million particles – roughly the number of particles in a handful of sand. Thus, many engineering scale processes are beyond the reach of DEM, while prototype scale problems require the use of oversized particles, which leads to scaling errors. The University of Melbourne Granular Mechanics Research Group effort is directed toward formulating a third class of models with the combined strengths of classical continua and DEM models and it is this hybrid type of models that are being studied in this research program through the use of micromechanics theory. The basic idea in micromechanics is to relate the microstructural/discrete properties (e.g. contact forces, contact moments, displacements and rotations), to macrostructural/continuum properties (e.g. stresses, couple stresses, strains and curvature) using a 'homogenization' or averaging procedure.

Over the past two years, this research has made important advances in developing the first breed of enriched continuum models for high resolution analysis of particulate media. The approach utilized fuses together techniques and principles from both modern and classical mechanics. Key micro-structures of only a few particles are 'smeared out' in traditional micromechanical homogenization methods. A novel feature of the new approach developed at the University of Melbourne is a high-resolution homogenization method, devised on the scale of a particle and its immediate void space. In essence, continuum properties are derived from a statistical average of the discrete interactions occurring between a particle and its first ring of contacting neighbors. In this homogenization scheme, the fabric is represented geometrically by a number of tessellation methods (*e.g.* Voronoi and Dirichlet). Fabric properties (such as void ratio, disorder, contact anisotropy, and number of contacts) of a particle assembly can be obtained from the statistics of cells in the tessellation representation; similarly, the evolution of fabric can be inferred from the evolution of the tessellated structure.

Figure 6: Bi-axial compression of randomly packed photoelastic discs: (a) before shear banding -the particle columns and direction of maximum stress transmission (force chains) are aligned with the direction of applied vertical compression; (b) a partially formed band emanating from top right corner. White lines were drawn in to indicate the boundaries of the shear band once fully developed; black buckled line drawn in to indicate the form of a buckled particle column. *Inside the band, particle columns and force chains are inclined to the vertical.*
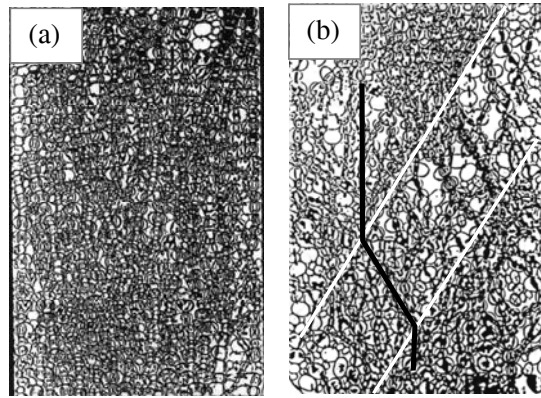
Using the homogenization scheme developed during a previous ARO project for 2-D assemblies of uniformly sized circular particles, constitutive laws have been developed that account for sliding and non-sliding contacts, rolling resistance at contacts, and loss of contacts. The analysis was performed assuming the granular material is a micropolar or Cosserat continuum, thereby allowing each material point to have both translational and rotational degrees of freedom. Furthermore, the use of strain dependent contact laws has resulted in a constitutive law that is able to predict the evolution of microstructural properties such as the degree and direction of contact anisotropy and contact force anisotropy.

V. TECHNOLOGY TRANSFER

Dr. Vladimir Ostashev, New Mexico State University, has been working with Army scientist, Dr. Keith Wilson on the understanding the scattering of acoustic waves by atmospheric turbulence. They have performed the first-ever analysis of the effects of turbulence on acoustic beam forming arrays; analyzed the effects of wind gusts on turbulence structure in the surface layer and developed the theory and numerical methods to directly solve closed-form equations for moments of propagating wave fields. Together they have published 4 papers including one on acoustic propagation through inhomogeneous, intermittent turbulence. They have been working with Dr John Noble at ARL/BED in support of the design and instrumentation of an acoustic tomographic array to measure volumetric winds and temperature in the atmospheric surface layer.

The Terrestrial Sciences program was very active in technology transfer during the past year. The 7th Annual Army Landmine Basic Research Technical Review Meeting and Workshop was held in Feb '04 supported by DOD JUXOCO and CECOM-NVESD Countermine Division for the broad dissemination of current Army and Navy intramural and extramural countermine R&D programs. The Terrestrial Sciences program worked cooperatively with the RDECOM European Office (ERO) in supporting the 2nd International Euro-Mediterranean Symposium on Laser-Induced Breakdown Spectroscopy that was held in Hersonissos, Crete from 30 Sept. to 3 Oct 2003 and the 3rd

International Conference on Laser Induced Breakdown Spectroscopy and Applications, LIBS2004 and the International Workshop on Security Applications of LIBS that was held in Torremolinos, Spain from 27 Sept to 1 Oct 2004. The Terrestrial Sciences program also worked closely with ERO to develop, organize, and support the Workshop on Scent Detection by Sniffer Animals and Electronic Noses that was held at the Sokoine University in Morogoro, Tanzania from 27-30 July 2004. Two advanced concepts workshops were conducted, a joint ARL-ARO/USACE-ERDC Workshop on Soil Moisture Remote Sensing Environmental Data Support that was organized and co-convened by Professors R. Bras and D. Entekhabi of the Massachusetts Institute of Technology and a Workshop on Desert Surficial Processes and Landscape Dynamics on Military Lands: Scientific Advances, New Challenges, and Technology Transfer jointly sponsored by ARO and the Desert Research Institute that was held in Zyzzx, CA from 17-21 Sept 2004.Under terms of an Army Research Office Memorandum of Agreement with Yuma Proving Ground, the YPG Tropic Regions Test Center sponsored a 2-week field research effort in Panama in support of an ARL-ARO-funded university research project at Colorado State University, University of Connecticut, and the University of Vermont. The primary objective of this fieldwork was to quantitatively study the geohydrology of the seven rivers of the upper Chagres River basin.

Researchers at the University of Connecticut delivered version 2.0 of the combined surface and groundwater gridded distributed simulation model *GSSHA* to the USACE-ERDC Coastal and Hydraulics Laboratory and PI Dr. F. Ogden worked closely with USACE staff to formulate potential application of the *GHHSA* model to the Greater Zab River basin in Iraq. This new version of the model contains the Sacramento soil moisture accounting routines widely utilized in the hydrologic engineering community. During the past two years, Dr. B. Minsker of the University of Illinois has developed otptimization methodologies, tools, and decision aids for the remediation of contaminated groundwater that have been tested and validated at the Umatilla Army Depot in Oregon. The University of Illinois researchers worked collaboratively with USACE Seattle District to characterize the uncertainty in the optimization model prior to its transfer for general USACE implementation. Researchers at the University of Mississippi engaged in the study of different acoustics-based approaches to the problem of landmine detection have transitioned an Acoustic Scattering Model and a Multiple laser Doppler Vibrometer Array to the CERDEC Night Vision and Electronic Sensors Directorate Precision Mine Neutralization with Confirmation and Localization Program. Dr. C. T. Kelley at North Carolina State University transitioned a new algorithm for adaptive temporal integration for non-smooth non-linearities and a new multilevel domain decomposition pre-conditioner algorithm to the USACE-ERDC Coastal and Hydraulics Groundwater Modeling Program. Finally, researchers at Duke University led by Professor L. Carin and Dr. L. Collins have had multiple technology transitions during the past year. The results of the foliage penetrating radar modeling work to a HPCMO project being executed jointly by ARL, AFRL, SAIC, and Boeing. Optimal experiment research has been transitioned to a new DARPA Integrated Sensors Program project being executed jointly by Johns Hopkins University, Lockheed Martin, and NAVAIR. Sensor models for adaptive landmine detection have been transferred to CERDEC Night Vision and

Electronic Sensors Directorate. A new 3-D non-linear inversion methodology has been transferred to the National Institutes of Health for breast cancer imaging.

VI. DIVISION STAFF

Dr. Kurt Preston
Associate Director (acting)
Environmental Sciences Division
Responsible for Defense Experimental Program to Stimulate Competitive Research and Defense University Instrumentation Program

Dr. Walter D. Bach, Jr.
Senior Program Manager
Environmental Sciences Division
Responsible for programs in atmospheric sciences.

Dr. Russell S. Harmon
Senior Program Manager
Environmental Sciences Division
Responsible for programs in terrestrial sciences and the ARO POC for landmine and unexploded ordnance detection and environmental quality research

Dr. Larry Russell
Program Manager
Environmental Sciences Division
Responsible for program examining environmental material interactions and the Multidisciplinary University Research Initiative Program

Rosa McCants
Administrative Support Assistant
Holds additional responsibility supporting University Research Initiatives.

I. PROGRAM OBJECTIVES

Basic research in the life sciences greatly increases our ability to conceptually identify and experimentally characterize unique materials and processes for future exploitation in engineered systems, and to understand and manipulate those aspects of biology that impact soldier sustainment, performance and survival. This research seeks to generate the means by which biological processes and products will provide materiel for Army use, to increase economic and environmental affordability by reducing maintenance and synthetic processing costs and by-products, to optimize human cognitive and physical performance, and to prevent the deleterious effects of chemical, biological, and physical agents from interfering with Army operations.

Research program activity in the life sciences is structured to emphasize an appropriate balance between capture of breakthrough scientific opportunities from the life sciences research community and alignment with Army and U.S. Department of Defense (DoD) science and technology objectives, and support of Army current and future demos and fielded items, where applicable. While aimed at enabling novel capabilities, program efforts focus on providing solid scientific underpinnings for biologically based technology contributions to fulfilling Army operational requirements. Within the framework of Army Transformation goals, emphasizing the Future Objective Force, it is expected that life sciences research will be making those contributions in the areas of force projection and protection, battle command, intelligence, maneuver, mobility, and logistics.

II. RESEARCH PROGRAM

A. General Information

Implementation of a strategy for meeting the above program objectives involves support of basic research in a number of subdisciplines including, but not limited to, biochemistry, biophysics, molecular biology, genetics, genomics, proteomics, cell biology, microbiology, physiology, pharmacology, and cognitive neurosciences, encompassing studies that range from the molecular, cellular, and systems levels through sensory perception and psychological studies on human performance. The U.S. Army Research Office (ARO) program of research support in these life sciences sub disciplines focuses predominantly on the needs of the Natick Soldier Systems Center and the Edgewood Chemical Biological Center (ECBC) of the Army Soldier Biological Chemical Command (SBCCOM), the Human Research and Engineering Directorate (HRED), Sensors and Electronic Devices Directorate (SEDD) and Weapons and Materials Research Directorate (WMRD) of the Army Research Laboratory (ARL), and the Night Vision and Electro-Optics Systems Directorate (NVEOSD) at Ft. Belvoir. There is also active coordination of common interests with several of the laboratories of the U.S. Army Medical Research and Materiel Command and the Corps of Engineers. Each major research area supports identified needs within appropriate Army mission areas. There is joint funding of several projects with other agencies. The Life Sciences also supports

some multidisciplinary research projects jointly with other ARO divisions. ARO-Life Sciences (ARO-LS) core program comprises research support in a number of subfield "thrust" areas, each representing an individual workpackage for ARO-LS Division (BH57-18-LS) funds, with additional support from other sources for projects falling within the purview of these subfields, or representing entirely separate workpackages.

B. Thrusts and Trends/Workpackages

ARO-LS Division activities are represented by the four individual "theme" or "thrust" areas identified within the existing ARO Broad Agency Announcement as the four ARO-LS "Workpackages" listed immediately below.

The **Biomolecular and Cellular Materials and Processes (BCMP)** workpackage is directed toward: (1) Fundamental studies to define structure-function relationships and biochemical interactions for enzymes, receptors and other macromolecules exhibiting mechanisms and properties uniquely relevant to synthetic and degradative pathways of interest to the military, including establishment of the foundations for manipulation and exploitation of biocatalysis, ribosomal and non-ribosomal biosynthesis to enhance permissiveness toward elaboration of useful biomolecular structures and cellular systems designed with "metabolic engineering" in mind, and (2) research to provide insight from nature on novel theoretical principles and mechanisms in sensory and motor function, as well as on materials with extraordinary properties, from biological sources. It includes not only initial molecular events, signal transduction pathways and integrated information processing for the powerful sensing capabilities exhibited in the biological world, but also self-assembly processes, hierarchical structure formation, and functional characterization of biomolecular materials such as those with potential "biomimetic" utility for nanometer scale fabrication or for energy and information transfer, among other possibilities.

The **Neurophysiology and Cognitive Neuroscience** workpackage covers research in the perception, performance and cognition subfields of neurophysiology and the cognitive neurosciences, covering several or all areas of electrophysiology, psychophysiology, sensory and perceptual physiology, computational neurobiology, psychophysics, neuropsychology, and integrative neurobiology. Specific examples include physiological, neuro-psychological and/or cortical/cognitive mechanisms underlying successful completion of complex task behaviors applicable to non-laboratory environments under non-ideal conditions, to include both amelioration of induced losses as well as enhancement in defined perceptual, cognitive and/or motor abilities. Investigations span the gamut from multi-unit recordings through evoked potentials and neuro-imaging technologies to humoral and psychological correlates of both central and peripheral nervous system function. Non-medically oriented research designed to elucidate the fundamental physiology underlying cognition and possible non-invasive methods of monitoring cognitive states and processes during normal activity is included. Perceptual and/or psycho physiological implications of mind-machine interfaces ranging from optimizing auditory, visual and/or somatosensory (haptic) display and control systems

based on physiological or psychological states through modeling of individual cognitive dynamics and decision making are included in this research area.

The Microbiology and Biodegradation (MB) workpackage represents basic research on microbial communities, the cell to cell communication leading to biofilm formation, and the changes in cell biochemistry, physiology and resistance when part of an organized community. Another area of research is the biochemical and physiological mechanisms underlying the biodegradative processes in normal, extreme, and engineered environments and includes fundamental studies on organisms in these environments, the properties of materials that make them susceptible or resistant to biological attack, basic concepts for anti–fungals, and studies of microbiological mechanisms with potential for contributing to the remediation of sites contaminated with toxic wastes. This includes research investigations in analytical microbiology (including microbial signatures), and in general microbial mechanisms with relevance to Army problems. Other areas of research include how to study organisms that cannot be grown in the lab, as well as research into methods to enhance the stabilization of military materiel, which would include methods to prevent microbial growth. Signal transduction, cell-to-cell communications and quorum sensing are important areas which can be studied in bacterial cultures especially in biofilms, as well as any research in how organisms can grow in unique (extreme) environmental conditions.

Molecular Genetics and Genomics (MGG) - This program emphasizes basic research in molecular genetics and genomics that will enable optimization of soldier cognitive and physical performance, soldier protection, and Army logistics. This includes human performance and protection under both normal conditions, and when affected by a variety of stressors that are likely to be encountered in battlefield situations, such as dehydration, heat, cold, sleep deprivation, fatigue, caloric insufficiency, microbial factors, and psychological stress. Genetic and genomic research areas include identification and characterization of gene function, gene regulation, genetic interactions, gene pathways, gene expression patterns, mitochondrial regulation and biogenesis, and nuclear and mitochondrial DNA replication, mutagenesis, oxidative stress, and DNA repair, also molecular responses to pathogens, pathogen identification, and pathogen inactivation, as well as host-pathogen interactions, and host components of infection and resistance to infection. This program is also interested in the biotechnology of microarrays, including both genomic- and proteomic-based platforms, for real time detection of pathogens or physiological states that would reduce or interfere with human performance. This program also supports development of new biomaterials and bioproduction methods, and other advances in biotechnology methods and applications

In much the same way as the LS program's prior 15 year support of biotechnology through earlier (1982-97) workpackage definitions attempted to both foster and exploit the area of biotechnology, each of these four current thrust areas outlined above continue to address the strong potential for emerging fundamental knowledge in **biotechnology** to make rapid and highly innovative contributions in the areas of materials, sensors, systems and processes, including striking advances for human, i.e. the soldier, as well as engineered systems application. Likewise, in keeping with the long-established ARO-LS

program interest in support of basic research impacting the areas of **human performance**, and **defense against chemical and biological threats**, and by extension, **soldier survivability**, there exists within each of these four workpackages, strong connections to issues regarding maintenance, and where possible, enhancement, of soldier health and performance.

A number of trends are visible throughout the ARO-LS program. For example, emphasis has been placed on biomolecular- and cellular-based approaches to detection because of the emerging recognition of the importance of contributions being made in the area of chemical sensing applications for mine and explosives detection, chemical and biological agent detection, and environmental monitoring. A DoD Multidisciplinary University Research Initiative (MURI) program in "Olfactory Sensing", initiated in FY98, finished its five year cycle, and one of the PIs has now been awarded the Nobel Prize in Physiology and Medicine. Support of basic research on high-selectivity biological threat detection has grown through its last year of support from the ARO-LS DoD MURI program in that area, with a substantial number of scientific accomplishments leading to commercial technology transition, including initiation and growth of small businesses addressing the area of biological detection. Research growing out of a biosensor-oriented project supported earlier within the LS program evolved through continued support from the ARO-CH Division and was recognized as one of the ten "Army's Greatest Inventions." These efforts reflect the particularly strong relevance of ARO-LS program activities to Army and wider national needs represented by the current situation with regard to counteracting biological and other forms of terrorism. Likewise, program emphasis continues in work related to better understanding, and the future possibilities of using, the opto-electronic or mechanical properties of unique biological or biologically derived molecules for sensor or other device application. Research in the areas of photodynamic proteins, olfactory processes, biomolecular recognition, and signal transduction in various modalities represents a substantial portion of the program and is expected to remain a strong contender for funding.

Because of its strong potential for supplying both insight and actual product or process formulation for novel structural and functional material architectures and advanced fabrication schemes, the area of biologically-inspired and biologically derived self-assembly and macromolecular construction continues its growth, incorporating studies of protein structure-function and the basis of highly reproducible association phenomena. Research here contributes in a major way toward elucidation of principles which, in turn, will be used in the future as lessons from nature in biomimetic and nanobiotechnological approaches to economically and environmentally favorable production of advanced materials. A number of projects addressed research that should significantly enhance our ability to produce large quantities of proteins containing tailor-made amino acids that do not exist in nature, not only for structure-activity studies, but also for specific biomolecular engineering applications, both aimed at energetically and economically favorable generation of useful functional materials. Tied to this overall thrust are exceptionally innovative projects aimed at understanding and exploitation of biologically derived processes for fabrication of nanoelectronic and nanomagnetic structures. Over the course of this past year, research addressing the interests of the Defense Department

portion of the National Nanotechnology Initiative, the Defense University Research Initiative in Nanotechnology (DURINT) program, was continued within the ARO-LS Division. An ARO-LS Division DURINT topic, "Biomolecular Control of Nanoelectronic and Nanomagnetic Structure Formation" entered its second year of support.

The research thrust described in the previous two paragraphs has been given a substantial boost most recently via the establishment of the newest Army University Affiliated Research Center, the Institute for Collaborative Biotechnologies (ICB) in August of 2003. The ICB is conducting unclassified scientific research in two areas of emphasis: (1) sensors, electronics and information processing and (2) technical fundamentals enabling development of advanced capabilities in these application areas. The University of California at Santa Barbara serves as lead UARC host for the ICB, with subcontracts to MIT and Cal Tech, two other universities that complement the expertise of the host institution and are fully integrated and networked into the host institution program. The vision for ICB is that it will serve as the network "hub" for conducting, assessing, coordinating and leveraging extramural cross-disciplinary biotechnology research on behalf of the Army.

In keeping with interests of the Corps of Engineers, and with the absence of such activity at the other services, research with potential impact on environmental bioremediation continued to have special attention, with additional support for projects aimed at a better understanding of the fundamental microbiological processes and chemical pathways that enable growth of microorganisms under unique environmental conditions. A number of studies address the degradative catalytic capabilities in relation to remediation of militarily relevant pollutants. ARO Biosciences research support in microbiological aspects of environmental remediation has increased since Air Force no longer maintains an active basic research program in this area. Two STTR Phase I contracts on biofilms were started in FY03; both have been approved for Phase 2 awards. More work in the area of cell-to-cell communication and quorum sensing needs to be supported. Additionally, congressional set-aside money was provided to fund a project which involves the use of biofilms to detect and perhaps remediate bioterrorist attacks involved in municipal and military water supply systems.

The new ARO thrust in "Neurophysiology and Cognitive Neurosciences" has matured into an active program with significant funding from both the ARO core budget as well as STTR and MURI activities. Research in the area of perceptual and cognitive neurosciences increased over the FY04 time frame with a total of nine single investigator grants, and two successful conferences. A MURI on human performance, "Optimizing Cognitive Readiness under Combat Conditions," involving coordinated oversight activities by ARO, HRED, ARI, MRMC, and SBCCOM is completing its fourth year. A further effort in "Human Sensemaking" as part of the HBCU Centers for Battlefield Capability Enhancements program is just starting. The research thrust area has become associated with an Army Strategic Research Objective (SRO), entitled "Enhancing Soldier Performance: The Core of Combat Effectiveness," and should continue to show growth in the future.

The past year has seen a continuing involvement of ARO-LS Division staff members with DARPA research program planning activities and other activities related to management of portions of the DARPA research project portfolio that parallel the life sciences interests of the Army Research and Development community. These not only take the form of typical DARPA agent functions, i.e., active program management, but also service as panel members for evaluative review processes for DARPA consideration of informal and formal proposal submission in various DARPA programs. Coordination of ARO and DARPA "interests in common" now include those for biomolecular motors; pathogen countermeasures; metabolic engineering/cell stasis; antibody replacement for biodetection; bio-fluidic chips; simulation of bio-molecular systems; preventing sleep deprivation; soldier self care; regeneration; cortical mechanisms in deception, brain-machine interfaces, engineered bio-molecular nano-devices and systems; and the bio:info:micro interface.

C. Research Investment

Approximately $20M from a variety of sources was invested in the **Biomolecular and Cellular Materials and Processes (BCMP)** workpackage for FY04. ARO-LS core program investment amounted to $786K for support of 10 research projects and 4 conferences. Very substantial leveraging of funds for research in this LS subfield was accomplished with support for this area supplemented to a large extent by other Army and DoD programs, including $417K partial support for the fifth and final year on an FY99 MURI on High Selectivity Detection of Biologicals. The MURI on Minimal Organotypic Cell System initiated in FY03 entered its first full year with $931K in MURI funds. The new Institute for Collaborative Biotechnologies UARC entered its first full year with $7.7M funds. Provision of just over $4.7M from DARPA enabled support of four research projects aimed at detection of unique odortype signatures, a program with strong connections to established BCMP core program interests. A DARPA program addressing feasibility studies for a research program geared toward biological engineering of nutritional state finished up. A DURINT research project on "Biomolecular Control of Nanoelectronic and Nanomagnetic Structure Formation" is in its fourth year of funding at $892K, and a special $100K per year OSD "Presidential Early Career Award in Science and Engineering" in that area of research is in its fourth year also. ECBC provided $167K for support of research in chemical and biological defense. Also included in this workpackage was $530K for a new Defense University Research Instrumentation (DURIP) project. A number of core and other program projects received no FY04 funding, but were still active under support from earlier multi-year awards in these programs. An ARO-LS infrastructure award in nanobiotechnology was supported previously with OSD Congressional funding was transferred to MRMC. University performers within the BCMP research support program include University of California, California Institute of Technology (Cal Tech), University of Texas, University of Virginia, Massachusetts Institute of Technology (MIT), University of Washington, Stanford University, and Princeton University, among others.

For **Microbiology and Biodegradation,** the ARO Life Sciences FY04 investment totaled about $5.7 million. Of this, core program funds amounted to slightly over $2.8 million,

in support of 10 research projects, which includes special money for biofilms of about $2M, as well as a little money from Air Force and Natick labs added on to specific contracts. These were supplemented with funds from a number of other programs. There was one DURIP for $307.5K and 1 STTRs at $384K (while another STTR is still being processed). There were 4 new minority schools and 3 new tribal schools funded this year for a total of $2,145K Among the performers within this workpackage are the University of Iowa, Montana State, the University of Idaho and Temple University. There are several DEPSCoR, and HBCU projects still active though with last year's money.

ARO Life Sciences core program investment in the **Molecular Genetics and Genomics** workpackage for FY04 was $774K for seven projects. Core program support was supplemented with funding from OSD and other DoD sources. This support included $28,249K from DARPA and $977K in SBIR and STTR funding. Support from all sources totaled $30M. This program supports 42 different research groups, including investigators at leading universities such as Rockefeller, Emory, the University of Washington (Seattle), and Stanford.

The **Neurophysiology and Cognitive Neurosciences** Program now supports nine single investigator projects with $856K of FY04 funds. The MURI on "Optimizing Combat Readiness under Combat Conditions" continues to be funded at approximately $1M per year. The HBCU-BCE project in Human Sensemaking is funded at $500K per year. Additionally, DURIP proposals at $253K, an STTR at $100K and two further HBCU projects at $363K were successfully competed and funded. Finally, external funding of $400K from DARPA was also attracted to the program in FY04 for four projects, and is proceeding well.

III. SPECIAL PROGRAMS

A. Multidisciplinary University Research Initiative (MURI)

The ARO-LS MURI on "High Selectivity Detection of Biologicals", initiated in June 1999 at the University of Texas, entered its last year. This MURI involves three fully integrated research efforts with the aim of providing the foundation for facile identification of pathological agents. It seeks to provide the fundamental information necessary for development of sensor arrays that can sensitively and accurately detect viruses, cells and macromolecules of biological origin, and incorporates work on: (1) engineering of high-performance receptors, (2) adapting receptors to sensors, and (3) manufacturing of sensor arrays. One of the co-PIs, Linda Buck, received the Nobel Prize for her pioneering work in this area. She was supported also with an ARO-LS core program award.

The objective of multidisciplinary research within a new MURI project under the topic "Minimal Organotypic Cell System," beginning its second year in FY04, was to emphasize the interface between biological sciences and the physical and engineering

sciences and to explore enabling fundamental science underpinning the possible use of vitally supported human immortal cell line-derived "mini-human" hybrid tissue-like collections of mature, differentiated cells. It was anticipated that these cell systems would exhibit sufficient tissue-differentiated function to mimic, at least in rudimentary form, a reproducible composite organotypic range of biochemically characteristic metabolic processes and genetic regulatory pathways, and physiologically normal stimulus-response properties. To the extent possible with any particular cell system, studies were to include issues of microsystems support for viability and stability enabling self-contained organotypic behavior. At the University of Michigan, multipotent immortalized stem cells will be used to create a multi-component bony organ *in vitro*, by providing appropriate spatial and temporal cues to direct these stem cells to acquire different fates in the forming organ. Hematopoietic stem cells will be subsequently introduced into the multi-component engineered bony organs to establish functional blood cell forming organs. These engineered bone marrow organs could provide an unusually sensitive physiological biosensor for the presence of various toxic agents, or have other applications of interest to the Army. The technologies developed to create these organs may also provide a template for the engineering of other complex, hybrid organs comprised of multiple cell types (e.g., liver, neural tissues).

Researchers participating in the MURI entitled, "Mitigating Stress, Workload, and Fatigue in the Electronic Battlefield" have made significant progress toward the development of stress theory by collectively employing multiple research approaches. They have elucidated the effects of diverse sources of real-world stress on spatio-temporal perception and the 'narrowing' that occurs under stress. MURI researchers have also begun to identify the limits of automation as a stress mitigation strategy, demonstrated a performance decrement under stressful combat simulation conditions (using paintball scenarios) due to remote command and control, and applying neuroergonomic insights toward the goal of using direct monitoring of physiological state to assess cognitive workload and readiness. The collective efforts described above have led to the surprising and important discovery of the 'table-top' tolerance limit phenomenon. This phenomenon indicates that even when stress levels are significantly high the performance remains relatively constant to a point of sudden incipient failure. This finding has significant implications for both our future work and planning for military operations in general. Identifying symptomatic characteristics at the edge of failure (e.g., progressive increase in performance variability) may provide a predictive marker that enables the identification of failing operators. It is also important to note that as a result of their efforts MURI researchers will not only be able to continue development of guidelines for operation under stress but also will have the capacity to directly contribute input, in the form of data regarding stress effects, into the IMPRINT model developed by ARL. These efforts will aid in the continued development of that tool.

B. Defense University Research Initiative in Nanotechnology (DURINT)

Within this special OSD program tied to the National Nanotechnology Initiative, under the ARO-LS topic entitled "Biomolecular Control of Nanoelectronic and Nanomagnetic Structure Formation," support for an interdisciplinary research project on "Genetically Engineered Proteins for Functional Inorganics" is in its third year at the University of Washington. It has among its primary aims a better understanding, a capacity to emulate, and to improve upon natural processes through combinatorial genetic engineering techniques to select proteins with high specificity to inorganic surfaces, and then to use biologically derived and biologically inspired pathways to manufacture a new generation of nanostructured multifunctional materials for DoD applications. The hope here is to be able to develop protocols for the formation of nanostructural units (quantum dots, nanowires, and tubes) and demonstrate their controlled assembly into useful 1-, 2-, and 3-D functional nanostructures for device applications (e.g. multispectral arrays, improved photovoltaics, hybrid molecular switches, and novel sensors).

C. University Affiliated Research Center (UARC)

In August, 2003, ARO made an award amounting to up to $50M for a five year period to a strongly integrated team of three universities in partnership with industry and the Army, for the newest Army UARC, the Institute for Collaborative Biotechnologies (ICB). The lead university host, University of California at Santa Barbara, in collaboration with California Institute of technology and Massachusetts Institute of Technology, and its industrial and Army partners will be conducting research in biotechnology addressing the overarching research concentration area of sensors, electronics and information processing, and its technical foundations, to understand and exploit biological mechanisms and to harness them for design and fabrication of new materials, devices and systems performance to equip the Army of the 21st century.

D. Small Business Innovation Research (SBIR) Program

ARO-LS has two phase II SBIRs working to identify and characterize genetic responses to pathogen exposure on a genomic scale. This technology will enable very early detection of biological warfare exposure and is expected to enable much earlier intervention, which should greatly reduce the impact of exposure to biowarfare agents on military and civilian personnel. The two companies working on this problem are Sun Biomedical Technologies (Ridgecrest, CA) and Illumigen Biosciences (Seattle, WA). This technology also has enormous potential to completely revolutionize human diagnosis, which should enable much earlier detection and prevention of all sorts of physiological conditions that could reduce or impair soldier performance. Both of these projects are also working closely with Walter Reed, and these collaborations benefit both the Army and the corporate investigators. Winners for a new SBIR "Innovative Hosts for Bacteriorhodopsin-Based Optical Memory" are in the process of being chosen.

E. Small Business Technology Transfer Program (STTR)

ARO-LS has two STTR programs in phase II. Integrated Genomics (Chicago) for $500K for "Bioengineered Proteins for Chemical and Biological Defense, Protection, and Decontamination," is sequencing, annotating, and building a free, publicly available database of the *Pichia pastoris* genome. *Pichia pastoris* is a budding yeast used by many commercial and academic labs for production and purification of recombinant proteins. Integrated Genomics is also constructing modified *Pichia pastoris* strains for more efficient protein production. Transwest Technology (Belgrade, MT) for $500K, entitled "Bioengineered Proteins for Chemical/Biological Defense, Protection and Decontamination," is investigating methods to generate transgenic chickens capable of expressing large amounts of recombinant proteins in egg whites, enabling economical commercial scale production. The other STTR by Arizona State University and AdveNSys, LLC will demonstrate neuromorphic control of a powered orthosis in an ambulating human subject. The development of this work will permit a qualitative improvement in the lives of all lower leg amputees. This technology can be marketed as components as well as expanded to other markets and uses, such as bilateral devices for motor/strength augmentation of troops or laborers. A third STTR by Quantum Applied Science and Research Inc has completed phase I and is awaiting a phase II application for research and development of a non-invasive gauge of human cognitive status. This system could be used in a broad range of military and civilian medical and psychological applications where automatic surveillance of cognitive state would be useful – for example, in airport traffic controllers or security monitors for industrial facilities. Two STTRs on the use of Biofilms for remediation purposes were approved for Phase 2 awards. If successful, remediation of contaminated sites should be improved. Previous work using free living organisms gave good results in the lab, but failed in the field, since bacteria do not occur as free living pure cultures in nature. Work with biofilms should correct this problem.

F. DARPA Biofluidic Chips Program (BioFlips)

Five of the more research-oriented projects within this program are managed in the ARO Life Sciences Division at five universities: Georgetown University, Cal Tech, University of California at Santa Barbara, Princeton University and the University of Texas. The goal of the BioFlips program, under overall management by Dr. Michael Krihak at DARPA, is to demonstrate technologies for integrated biofluidic microprocessors capable of on-chip reconfiguration and self-calibration via feedback control. The prototypes developed will be capable of on-chip sample-to-answer biological fluid assays, and will form the basis for the future goal of real-time unobtrusive monitoring and control of a person's health parameters, a particularly important area of research in these times of military operations overseas and homeland threats from terrorist use of chemical or biological agents.

G. DARPA Unique Signature Detection Program (USD)

With funds provided by Dr. Lisa Porter in the Advanced Technology Office (ATO) at DARPA, a number of research awards were initiated by ARO within the BCMP subfield for this new program that addresses issues of relevance to the Army. Representing an important foundation within this DARPA program, support of these four projects will contribute strongly to the overall goal of the program, to determine whether genetically-determined odortypes can be used to identify specific individuals, and if so, to develop the science and enabling technology for detecting and identifying specific individuals by such odortypes. The institutional teams involved are: (1) Monell Chemical Senses Center, the University of Pennsylvania and Battelle Labs, (2) Draper Laboratory and the Johns Hopkins University, (3) Konrad Lorenz Institute (Austria), University of Newcastle (UK), Indiana University and University of Delaware, and (4) Research Triangle Institute.

H. DARPA Gut Seedling Program

This new DARPA program provides support for three feasibility studies. The goal of basic research in this program is to generate results addressing the possibility that enabling technology might in the future allow soldier sustainment through, for example, microbial gut flora and/or other enzymatically based digestion of biomass material as a supplement, or in extreme survival conditions, as a primary meal. As such, this research is relevant to the interests of Army and other DoD components that field an operational force that could benefit from this available energy source. Research is supported at the University of Washington, Genencor Inc., and Georgia Institute of Technology.

I. DARPA Pathogens Countermeasures (PC)

ARO LS manages 15 basic research projects in this program. The focus of this program is the development of revolutionary, broad-spectrum medical countermeasures and/or advanced medical diagnostics against exposure to significantly pathogenic microorganisms, or their products. This effort is a key component of DARPA's overarching goal to eliminate the threat of biological and chemical weapons in the planning and conduct of US military operations. While no defense can stop an adversary from unleashing biological or chemical weapons, a sufficiently robust array of pathogen and chemical defenses and countermeasures-deterrents in their own right-will reduce the damage resulting from biological or chemical weapons used in a particular operation. DARPA's UPC program emphasizes the development of pathogen countermeasures and advanced medical diagnostics having the greatest impact on the protection of uniformed war fighters and personnel who support them during military operations. This program was briefed to Vice President Cheney in 2002.

J. DARPA Preventing Sleep Deprivation (PSD)

ARO LS manages six basic research projects in phase II of this program. As combat systems become more and more sophisticated and reliable, the major limiting factor for

operational dominance in a conflict is the war fighter. Eliminating the need for sleep during an operation, while maintaining the high level of both cognitive and physical performance of the individual, will create a fundamental change in war fighting and force employment. Such a capability has the potential to disrupt enemy OPTEMPO, increase the effectiveness of small footprint military forces and shorten the duration of conflict. The logistics impact of this capability is realized in the time of delivery of personnel, materiel and weapons platforms to overseas theaters of war or conflict. Because of the ubiquitous contribution of enhanced alertness to the armed forces, this technology advantage is not restricted by service roles and missions.

The goal of the Preventing Sleep Deprivation (PSD) program is to identify approaches that extend the performance envelope of the war fighter. The capability to resist the mental and physiological effects of sleep deprivation will fundamentally change current military concepts of "operational tempo" and contemporary orders of battle for the military services. The program will develop a number of different strategic approaches to prevent the effects of sleep deprivation over an extended period of time, nominally set at 7 days (24/7). These approaches will capitalize on emerging concepts in neuroscience, neurobiology, cognitive psychology, cell signaling/regulation, non-invasive imaging technologies and novel mathematical approaches to modeling and analysis. In short, the capability to operate effectively, without sleep, is no less than a 21st Century revolution in military affairs that results in operational dominance across the whole range of potential U.S. military employments.

K. DARPA Soldier Self Care (SSC)

The goal of the Soldier Self Care (SSC) program is to optimize the ability of the warfighter to remain effective in combat situations. ARO manages a $929K research effort at Rinat Neurosciences Inc. to develop better pain therapeutics. Morphine is currently used on the battlefield to control pain, however morphine-treated warfighters are incapable of fulfilling their duty, or even defending themselves. Rinat is developing a novel pain therapeutic that has potential for effective pain relief without interfering with the cognitive processes of the warfighter.

L. DARPA Accelerated Anthrax Therapeutics (AAX)

The goal of the Accelerated Anthrax Therapeutics program is to bring anthrax countermeasures through FDA approval so that they can be effectively used by the Armed Forces. ARO currently manages five efforts ($11.8M) in this program. This year Coley Pharmaceuticals, one of the performers supported by this program, filed an IND (Investigational Drug Use) with the FDA to use CpG 7907 as an adjuvant for the anthrax vaccine. Increasing the effectiveness of the anthrax vaccine is expected to reduce the incidence of side effects and lead to increased acceptance of the vaccine among warfighters and the general public. It should also shorten the vaccination regimen, enabling warfighters to be protected earlier.

M. DARPA Checkpoint Screening Program

ARO LS manages 4 programs in this effort to determine indicators that would permit stand-off detection of individuals attempting to evade or confound security checkpoint procedures. These efforts include basic research into cultural determinants that influence responses to checkpoint situations, physiological changes that indicate deception attempts and implementation of virtual environments to act as test beds for such research.

N. Defense University Research Instrumentation Program (DURIP)

With provision of FY04 OSD funds for purchase of research equipment used in university efforts relevant to Army Research Office mission, this program supported research in various areas of interest to ARO-LS. There are four new projects funded over $1.3M. Five others supported with three-year funds provided in prior years remained active.

O. Defense Experimental Program to Stimulate Competitive Research (DEPSCoR)

There was one new DEPSCoRs started in FY04 for $ 440K at University of Southern Maine. Seven DEPSCoRs with previous year funding are still active. This project at University of Southern Maine investigates the genotoxicity of depleted uranium in human bronchial cells.

P. Historically Black Colleges and Universities/Minority Institutions (HBCU/MI)

The ARO HBCU/MI program for FY04 provided grants for individual investigator support of research at five colleges and universities. The total FY04 investment was $1,328K. The schools supported were a mix of small and large institutions and historically black schools, as well as other minority colleges and universities. This year, beside the regular HBCU/MI program, there was a separate program for Tribal Colleges & Universities (TCU). ARO LS supports the leading spider silk researcher in the country through this program. In total, including the programs that cover multiple years, Life Sciences has $9.7M in active grants committed to Black, Hispanic, Tribal and other minority institutions.

IV. SCIENTIFIC ACCOMPLISHMENTS

Creating Fluid and Air-Stable Solid Supported Lipid Bilayers
Professor Paul Cremer, Texas A&M University

Solid supported lipid bilayers possess a unique combination of physical properties, which make them well suited to serve as cell membrane mimics. Chief among these is the two-dimensional fluidity of the individual lipid molecules. Such mobility is crucial for studies of cell signaling, pathogen attack, trafficking of lymphocytes, as well as the inflammatory response. Mobility is required because all these processes involve

multivalent ligand-receptor attachment, which relies on the reorganization of cell surface constituents. When fully hydrated, supported lipid bilayers can be employed as sensor platforms; however, these systems are quickly destroyed upon exposure to the air/water interface, and therefore must remain underwater at all times. Several attempts have been made to overcome this limitation, but have not met with much success. It would be highly desirable to create solid supported bilayers which could be insensitive to the air/water interface, yet still maintain complete fluidity. In addition, if these bilayers could be dried and stored, it would substantially increase their utility as sensing platforms. ARO-LS PI Paul Cremer and his group have introduced a step toward the goal of rugged bilayer formation and have provided some mechanistic insights into the process. Their method of bilayer preservation requires no substrate modification and can be performed using commercially available reagents. The bilayer retains its property of lateral fluidity, even when removed from bulk water. This has potentially important implications in the field of biosensing. If rugged supported bilayers could be preserved and stored for later rehydration, complex sensor arrays could be manufactured at dedicated facilities and then later employed in the field.

Figure 1: Creating Fluid and Air-Stable Solid Supported Lipid Bilayers
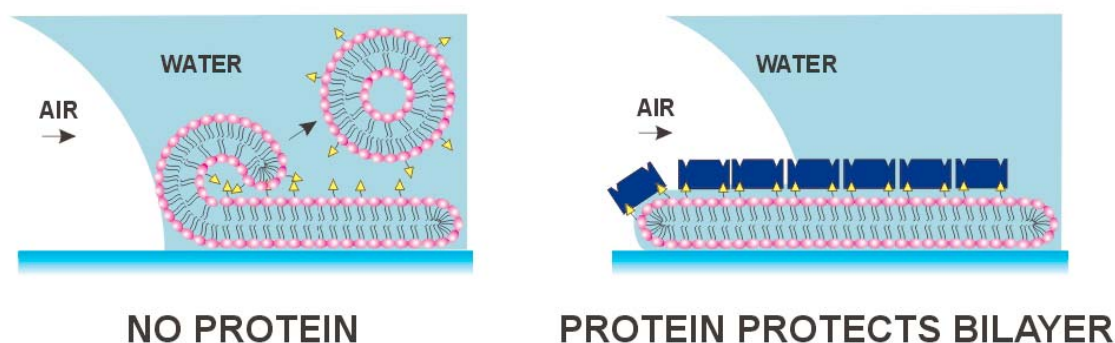
Solid supported lipid bilayers are rapidly delaminated when drawn through the air/water interface. They have discovered that a close packed monolayer of specifically bound protein prevents this process. The protection mechanism worked in two ways. First, when protein-protected bilayers were drawn through the air/water interface, a thin bulk water layer was visible over the entire bilayer region, thereby preventing air from contacting the surface. Second, a stream of nitrogen was used to remove all bulk water from a protected bilayer, which remained fully intact as determined by fluorescence microscopy. The condition of this dried bilayer was further probed by fluorescence recovery after photobleaching. It was found that lipids were not two-dimensionally mobile in dry air. However, when the bilayer was placed in a humid environment, 91% of the bleached fluorescence signal was recovered, indicating long range 2-D mobility. The diffusion coefficient of lipids under humid conditions was an order of magnitude slower than the same bilayer under water. Protected bilayers could be rehydrated after drying, and their characteristic diffusion coefficient was reestablished. Insights into the mechanism of bilayer preservation were suggested in a recent publication.

Isolating Phage Lytic Enzymes to Destroy Bacteria that Cause Infectious Diseases and Can Be Used as BioWarfare Agents
Dr. Vince Fischetti, Rockefeller University and Enzybiotics

In the last several years the importance of phage therapeutics has become widely recognized. NIH funding for phage research was discontinued in the 1950s upon the recommendation of the American Medical Association. The short-sightedness of this advice is now recognized with the spread of antibiotic resistant strains of pathogens, and limited treatment options for bacterial infections. In addition, eastern bloc countries did not heed the advice of the American Medical Association and are now the leaders in clinical production of phage therapeutics. ARO supports U.S.-based research to develop phage enzymes into FDA-approved alternatives to antibiotics. Unlike antibiotics, phage enzymes are very specific, and thus not subject to the horizontal gene transfer problems and the transfer of resistance that plague conventional antibiotics. With the usefulness of conventional antibiotics decreasing, it is critical that alternative therapeutics be developed.

ARO PI Vince Fischetti has exploited a bacteriophage that infects the anthrax bacterium. This virus synthesizes a lysin enzyme that punches holes in the bacterial cell wall. The enzyme has been tested in mice and shown to be effective at protecting the mice from anthrax. As summarized in his Nature article: "The dormant and durable spore form of *Bacillus anthracis* is an ideal biological weapon of mass destruction. Once inhaled, spores are transported by alveolar macrophages to lymph nodes surrounding the lungs, where they germinate; subsequent vegetative expansion causes an overwhelming flood of bacteria and toxins into the blood, killing up to 99% of untreated victims. Natural and genetically engineered antibiotic-resistant bacilli amplify the threat of spores being used as weapons, and heighten the need for improved treatments and spore-detection methods after an intentional release. We exploited the inherent binding specificity and lytic action of bacteriophage enzymes called lysins for the rapid detection and killing of *B. anthracis*. Here we show that the PlyG lysin, isolated from the phage of *B. anthracis*, specifically kills *B. anthracis* isolates and other members of the *B. anthracis* 'cluster' of bacilli *in vitro* and *in vivo*. Both vegetative cells and germinating spores are susceptible. The lytic specificity of PlyG was also exploited as part of a rapid method for the identification of *B. anthracis*. We conclude that PlyG is a tool for the treatment and detection of *B. anthracis*." In addition, these enzymes show great potential for specific detection of bacterial biowarfare agents. The anthrax enzyme can detect as few as 100 spores. Fischetti started a new biotechnology company, Enzybiotics, to commercialize phage therapeutics, and his research has been featured on the front page of the New York Times and on the cover of Nature. Enzybiotics has explored several bioproduction systems in depth, and future commercial production of this enzyme looks promising.

Discovery of Novel Antifungal Compounds Produced as Result of Plant-Microbe Interactions
Dr. Don Crawford, University of Idaho

The objective of this research was to discover new microbially-produced antifungal compounds useful for protecting military materials in the field from fungal biodeterioration.. As organisms have built resistance to the few antifungals available it is necessary to find alternatives. Dr. Crawford decided to look in unique places, i.e. the deserts of western states. Not many bacteria grow in the desert except around the rhizospheres of plants. He found large numbers of actinomycetes growing in the rhizospheres of sagebrush, isolated them, and tested for antifungal activity. He found novel antifungal compounds from newly identified bacteria. He developed a hydroponic culture system, since these compounds are not produced without some factor from the plant, though he has now developed a simpler system using an exudate from the rhizosphere in place of the whole plant. He is purifying a few of these low molecular weight, broad spectrum, stable compounds. When purified, they will be tested in realistic settings.

Figure 2. **Hydroponic Culture System**
A.   Reservoir with medium
B.   Sterile barrier
C.   Plant culture container
         (bottle with the bottom cut out)
D.   Petri dish used as lid
E.   Sand, wet with medium
F.   Aseptic sampling apparatus
         with flask
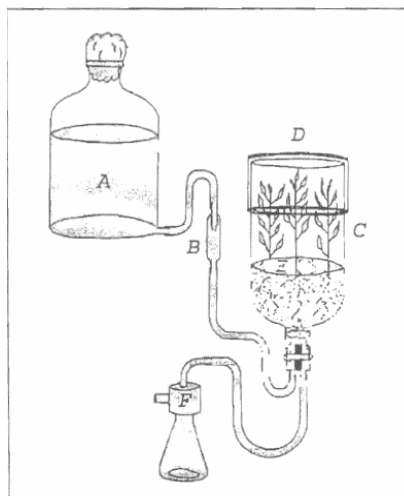
Oxygen and Water Permeabilities across Archael Liposomal Membranes
Dr. Parkson Chong, Temple University School of Medicine

The organism that Dr. Chong has chosen to work with lives at high temperature (65-85C) and at low pH (2.4-3.0). How this organism survives under these harsh conditions is in large part due to the membrane. Archael membranes are different from bacterial membranes. So, the PI set out to examine the permeability, stability, and molecular packing of the liposomal membranes. The membranes are composed of a polar lipid fraction which is a mixture of bipolar tetraether bonds. He found tight and rigid packing with a low proton and water permeability. The lipid is stable at least 6 months at various temperatures. The goal of Dr. Chong's work is to have lipid coatings that will protect surfaces from chemical and oxidative-mediated degradation.
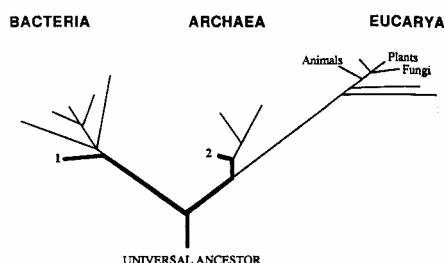
Figure 3
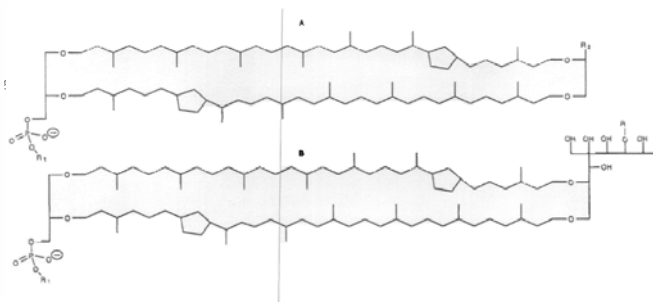
Figure 4

***In Situ* Genetic Modification of Natural Microbial Communities with Genes of Value for Bioremediation**
Dr. Ronald Crawford, University of Idaho

Dr. Crawford demonstrated for the first time the successful natural transformation of bacteria with clay-bound free DNA for improving a bioremediation process. He transferred catabolic genes specific for the compounds to be degraded to a natural, indigenous microbial population. This transfer of genetic material occurs all the time in nature, but the ability to direct the results for a specific use is a step forward. The PI also used a genetic algorithm to optimize natural processes by complex microbial consortia (biofilms), being able to change some of the organisms in the complex with degradative genes. A patent has been filed for this latter project.

Molecular Database Construction and Mining: A General Approach to Unconventional Pathogen Countermeasures
Dr. Yuan-Ping Pang, Mayo Foundation

Dr. Pang developed a new supercomputer approach for modeling proteins with extremely high resolution, enabling him to rapidly identify therapeutic agents for countering chemical and biological weapons. Recently he has used his technology to successfully

obtain more effective acetylcholinesterase reactivators, irreversible adenovirus proteinase inhibitors, and inhibitors of anthrax lethal factor. (See figure 5 below.) A commercial company has been established to commercialize this research and to extend its applicability.
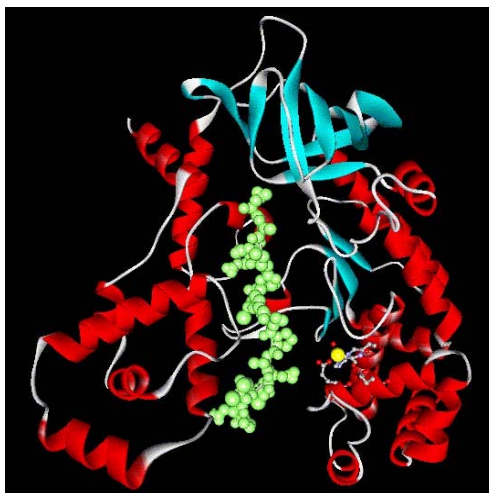
Figure 5. A Computer Refined 3D Structure of the Active Site of Anthrax Bound with a Substrate (green) and the Zinc Ion (yellow).

Time-frequency Computational Model for Echo-delay Resolution in Sonar Images of the Big Brown Bat, *Eptesicus fuscus*
Drs. Nathan Intrator and Leon N Cooper , Brown University

Mammals that prey in the dark have remarkable auditory systems. Some bats use their auditory systems to achieve full 3D navigation capabilities and prey discrimination, based on resolution in the sub-millimeter range. Likewise, some dolphins utilize their auditory systems to achieve a combination of 3D navigation and internal object examination that far exceeds the abilities of our current ultrasound and underwater sonar technology.

Professors Nathan Intrator and Leon N Cooper and their colleagues at the Institute for Brain and Neural Systems at Brown University, have been studying these capabilities, and have discovered that a variety of techniques including the sophisticated fusion of information from multiple sonar pings may be responsible for their remarkable performance in low signal-to-noise environments. They have developed a mathematical model that demonstrates how this can be done for underwater target recognition as well as ultrasound applications. They have recently submitted three patents on this biologically motivated technology and are looking for ways to utilize the technology in homeland security, medical and oil exploration applications.

V. TECHNOLOGY TRANSFER

Electrokinetic Focusing Biofluidics Technology for Biosensors
Dr. Carl Meinhart
Transferred to: ARL-SEDD
Application: Biochemical sensing technology

Antibody Display Technologies
Drs. George Georgiou and Brent Iversen, University of Texas
Transferred to: Elusys
Application: Biological Detection

Structure-Directing Synthesis of Metal Oxides and Related Materials
Dr. Daniel Morse, University of California at Santa Barbara
Transferred to: Patent
Application: Unique biologically derived means of fabrication of electronic materials

Peptide Ligands with Enhanced Binding Specificity for *B. Anthracis* Spores
Dr. Chuck Turnbough, University of Alabama
Transferred to: Center for Disease Control, Sandia National Laboratory, Los Alamos National Laboratory, MIT Lincoln Laboratory, Natick Soldier Center, Beckman Coulter, 3M Company, Constellation Technologies.

Constructing Efficient Microbial Consortia Using a Genetic Algorithm
Dr. Ronald Crawford, University of Idaho
Transferred to: Patent
Application: Forming biofilms to perform specific tasks

Combinatorially Selected Inorganic Binding Polypeptides as Molecular Erectors for Nano- and Bionanotechnologies
Dr. Mehmet Sarikaya, University of Washington
Transferred to: Patent
Application: Advanced microelectronics and photonics

Aptamer Based Amplification
Dr. Ken Clinkenbeard, Oklahoma St. U.
Transferred to: MIT licensed Fluorescing Polymer Technology - Nomadics, Inc, Stillwater, OK
Application: Sensors for BW agents

Novel Antiviral Drugs: Small Molecule Inhibitors of the NP3 Serine Protease of Dengue 2 Virus
Professor Yuan-Ping Pang, Mayo Foundation, Rochester
Transferred to: Patent
Application: New compounds to treat Dengue 2

Using Bacteriophage Lytic Enzymes to Specifically Destroy Biological Warfare Agents
Dr. Vincent Fischetti, Rockefeller University
Transferred to: Enzybiotics
Application: Utilization of Bacteriophage Lytic Enzymes to Treat Biological Warfare Exposure

New Adaptive Sonar Algorithms
Dr. Leon Cooper, Brown University
Transferred to: Patents
Application: Design of emitting and sonar receiving systems

Intratesticular Administration of Transposon-Based Vectors
Dr. Ken DeBoer, TransGenRx
Transferred to: Patents
Application: New production technologies for bioproducts

CpG as an Anthrax Adjuvant
Dr. Art Krieg, Coley Pharmaceuticals
Transferred to: AF
Application: More effective and faster acting anthrax vaccine

VI. DIVISION STAFF

Dr. Elmar T. Schmeisser
Associate Director (acting)
Chief, Neurophysiology and Cognitive Neurosciences

Dr. Robert J. Campbell
Senior Scientist
Chief, Biomolecular and Cellular Materials and Processes

Dr. Sherry Tove
Chief, Microbiology and Biodegradation

Dr. Micheline Strand
Chief, Molecular Genetics and Genomics

Dr. Leo Parks
Consultant, Microbiology

Lin Lindley
Administrative Support Assistant

I. PROGRAM OBJECTIVES

Advanced materials provide the means to improved firepower, mobility, armaments, communications, personnel protection, and logistics support for the Army. The objectives of the Materials Science Program include work in the following areas:

- Developing materials and processing approaches that lead to improved properties or special combinations of properties (e.g., organic and inorganic materials exhibiting unique electromagnetic and strength properties).

- Establishing the means to predict, realize, and retain important engineering properties in advanced materials and structures with greater reproducibility and reliability in order to increase combat readiness and extend service life.

II. RESEARCH PROGRAM

General Information

Advanced materials will be an integral part of the emerging technologies and breakthrough opportunities that impact virtually all U.S. Army mission areas in the future, including communications, combat service support, battle command, intelligence and electronic warfare, fire support, close combat (heavy and light), aviation, air defense, engineering and mine warfare, and nuclear, biological, and chemical (NBC) defense. Materials research is currently leading to the development of new classes of materials with increased strength and toughness, lighter weight, greater resistance to combinations of severe chemical and complex loading environments, and improved optical, magnetic, and electrical properties. These advances provide new possibilities for upgrading and lightening Army systems, as well as providing the basis for realizing new weapon and platform concepts in the future. In addition to the discovery of new materials with improved properties, the Materials Science Program also has the goal of reducing the high manufacturing costs of Army materiel and components while improving the reliability and extending the useful life of these products and systems.

The overall goal of the Materials Science Division continues to be the elucidation of the fundamental relationships that link composition, microstructure, defect structure, processing, and properties of materials. This knowledge enables the research program to continue to generate new discoveries that will make it possible for the U.S. Army to maintain the overall technological edge required for the future. This is achieved by supporting research in the following four subfields:

Synthesis and Processing of Materials - The program on Synthesis and Processing of Materials focuses on the use of innovative approaches for processing high performance structural materials reliably and at lower costs. The emphasis is on the design and fabrication of new materials with specific microstructure, constitution, and properties.

Research interests include experimental and theoretical modeling studies to understand the influence of fundamental parameters on phase formation, microstructural evolution, and the resulting properties, in order to predict and control materials structures at all scales ranging from atomic dimensions to macroscopic levels. Current thrusts in this subfield include: non-equilibrium materials processing; powder synthesis and consolidation; novel processing of ceramics, polymers, metals and composites; welding and joining of materials including composite materials; and utilization of microstructural, compositional, or other unique signatures that provide non-destructive in-situ feedback process control to enhance product reproducibility and quality.

The research in this subfield addresses Army needs for: lightweight alloys and composites for vehicle structures, lightweight armaments, airframes, and bridging; advanced ceramics for improved armor; improved materials and processes for joining of components; high-density metals for kinetic energy penetrators; fabrics and polymeric body armor; thermal and acoustical insulating foams; materials for gun tubes, and directed energy weapons.

Mechanical Behavior of Materials - The program on Mechanical Behavior of Materials seeks to address the fundamental relationships between the structure of materials and their mechanical properties as influenced by composition, processing, environment, and loading rate. The program emphasizes research with the potential to dramatically enhance the mechanical properties of known materials systems and research that seeks to develop innovative new materials with unprecedented combinations and formulations of mechanical, and other complementary, properties. Critical to these efforts is the need for new materials science theory that will enable robust predictive computational tools for the analysis and design of materials subjected to a wide range of specific loading conditions, particularly theory which departs from standard computer algorithms and is not dependent upon tremendous computational facilities. The primary research thrust areas of this program include: (a) high strain-rate phenomena (e.g., experimental and computational analysis of the physical mechanisms which govern deformation in advanced materials, lightweight damage tolerant materials); (b) property-focused processing (e.g., materials science theory to predict the range of properties attainable with advanced processing methods, novel approaches for enhancing specific toughness); and (c) tailored functionality (e.g., innovative materials containing unique and specifically designed chemical and biological functionalities and activities while maintaining, or preferably enhancing, requisite mechanical properties).

Research in this subfield addresses Army needs in the areas of: lightweight composite materials for vehicle structures, gears, and bearings; damage tolerant multifunctional and multi-threat capable materials for the next generation of armor systems; advanced ceramics, polymers, composites, and fiber weaves for the soldier protective ensemble; amorphous materials for penetrator and fatigue/environmentally resistant structures; biomimetic materials for damage sensing/self healing structures; and advanced computational techniques for predictive and materials design capabilities.

Physical Behavior of Materials - The program on Physical Behavior of Materials seeks to provide an improved understanding of the fundamental mechanisms and key materials and processing variables that determine the electronic, magnetic and optical (EMO) properties of materials and affect the reliability of EMO devices. Emphasis is on research that facilitates the nanostructuring of materials to realize the materials-by-design concept where new and unique materials are constructed on the atomic scale with application-specific properties. This includes research on understanding the underlying thermodynamic and kinetic principles that control the evolution of microstructures; understanding the mechanisms whereby the microstructure affects the physical properties of materials; and developing insight and methodologies for the beneficial utilization and manipulation of defects and microstructure to improve material performance. Major thrusts in this subfield include: (i) electronic materials - materials for microelectronics and packaging, including the fabrication and processing of semiconductors, interconnects and device structures, and the characterization and control of trace impurities, defects and interfaces in semiconductors, (ii) magnetic materials - bulk and thin-film processing of magnetic materials and fundamental studies on magnetic coercivity and spin dynamics, and (iii) optical materials – new material approaches and processing methods for development of detectors, lasers, nonlinear optical materials, refractive and diffractive optics, and optical windows and coatings. Research to improve the long-term stability of EMO materials and to develop multifunctional or smart EMO materials is also being conducted.

The research addresses vital Army needs including, development of semiconductor and field-tunable materials for data/image processing, target acquisition and communications systems; hardening of electronic and optical systems against radiation damage; and improvement of detector and thermoelectric materials for night-vision systems.

Materials Design - The materials design program seeks to tailor material properties to meet application-driven requirements. The research seeks to strengthen the coupling of experimental research to theory and modeling, and provide for enhanced predictive capabilities. The goal is to predict and control material behavior during processing and operation, to predict property changes over time, to optimize performance and reliability, and to reduce cost and time to development. One area of emphasis is surface and interface engineering in support of materials integration and multifunctional material development. The other area of emphasis is the development of in-situ and ex-situ analytical methods that afford the spatial resolutions and sensitivities needed to advance our understanding of the behavior of materials under relevant processing and operating conditions. Specific areas of interest include investigations of high temperature materials and their relevant degradation modes; development of adaptive or smart materials capable of responding to internal or external stimuli; study and development of self-repair or self-healing mechanisms in materials; development of approaches for in-situ monitoring of material performance and health; and investigations of novel methods for large-scale assembly of nanomaterials.

Thrusts and Trends/Workpackages

Currently, six research themes are receiving special emphasis with the division. They are interdisciplinary in nature and are intended to foster strong cooperation across ARO divisions, as well as with the Army laboratories and other agencies. Some of these areas also have high U.S. Department of Defense (DoD) visibility. The special thrusts (not in any order of priority) include:

Synthesis and Processing – focuses on the development of improved understanding of the interrelationships among processing, microstructure and properties of advanced materials, and on development of innovative approaches to the synthesis of reliable, low cost, and environmentally friendly new materials.

Deformation and Toughening Phenomena – focuses on the investigation of material behavior under static, cyclic, and dynamic loading conditions and the fundamental aspects of chemistry and structure that influence material toughness with an emphasis on understanding and optimizing the response of advanced materials and composites to complex loading conditions that are imposed on high performance weapons systems.

Defect Engineering – focuses on understanding the underlying thermodynamic and kinetic principles that control the evolution of defects in materials, identifying the limits that defects impose on synthesis and performance of materials; and developing insight and methodologies for the utilization and manipulation of defects to produce materials with new and enhanced properties.

Interface Engineering and Surface Modification – focuses on the investigation of new methods and approaches for tailoring application specific properties of materials through modification of interfacial and surface structures of similar and dissimilar materials.

Computational Materials Modeling and Design – focuses on the development of computational materials theory to enable novel simulations of processing and ultimately properties of advanced materials and by developing theories which predict the interrelationships among properties specifically selected to meet Army requirements.

Multifunctional and Smart Materials – focuses on developing new classes of materials with unique and complementary combinations of material properties and functions, such as chemical and biological activities and functionalities, or the methodology necessary to integrate function into structural materials.

III. SPECIAL PROGRAMS

A. Army Programs

The Materials Science Division manages programs funded under the Army Small Business Innovation Research (SBIR) Program, the Small Business Technology Transfer Research (STTR) Program, the Historically Black Colleges and Universities/Minority

Institutions (HBCU/MI) Program, the Young Investigator Program, and the Institute for Soldier Nanotechnologies.

1. **Small Business Innovation Research and Small Business Technology Transfer Research Programs -** These programs are intended to stimulate technology innovation and transfer and strengthen the role of small business to meet DoD research and development needs.

The division manages two Phase I SBIR programs, these programs are:

- Ocular Scanning Instrumentation Diagnosis of Induced Trauma from Thermobaric Weapon Detonation, Dr. Lance Molnar of MD Biotech, Inc.

- Surrogate Lung Tissue as a Platform to Test TBX Weapons, Dr. Anatoly M. Kachurin of Sciperio, Inc.

The division manages three Phase II SBIR programs, these programs are:

- Novel Technology for High Energy-Absorbing Metallic Foams and Structural Components - Lev Tuchinskiy at Materials & Electrochemical Research Corporation

- Development of Highly Reinforced Amorphous Metal Matrix Composites - Ranji Vaidyanathan at Advanced Ceramics Research, Inc.

- Visible Lasers on Silicon for Optical Interconnection Applications, Dr. Matthew Erdtmann, Amber Wave Systems Corporation

The division also manages five Phase I STTR programs, these programs are:

STTR Phase I

- A Novel Bio-Appliqué for Corrosion Protection – Vladimir Gilman at Foster - Miller and Professor Thomas K. Wood at the University of Connecticut

- Corrosion Protection of Aluminum Aerospace Alloys by Biofilm Appliqués – Margarita Kharshan at Cortec Corporation and Dr. Peggy J. Arps at the University of California, Irvine

- Nanostructured Thermoelectric Composites, David Carnahan, NanoLab, Inc. with Drs. Gang Chen and M. S. Dresselhaus of Massachusetts Institute of Technology and Dr. Z. F. Ren of Boston College

- Nanostructured Thermoelectric Composites, Dr. David Pickrell, Omega Piezo Technologies, with Professors John Badding, Gerald Mahan, and Ayusman Sen, Pennsylvania State University

- Nanocomposites with Independently Controlled Properties of the Thermoelectric Materials for High Figure of Merit, Dr. Jae Ryu of Aspen Systems, Inc. and Professor Terry Tritt of Clemson University

2. **Young Investigator Program (YIP) -** The Division funded two Young Investigator Programs in FY04. This program supports the research of outstanding young faculty members at U.S. institutions of higher education who have recently completed their Ph.D. These single investigator programs are:

- Smart Core-Shell Nanowire Architectures for Multifunctional Nanoscale Devices, Professor Jonathan Spanier, Drexel University

- Automatic Healing of Damage in Polymer Matrix Composites, Professor Kessler, University of Tulsa

B. Director, Defense Research and Engineering Programs, Office of Secretary of Defense

1. **Multidisciplinary University Research Initiative (MURI) -** The Materials Science Division manages five programs in the areas of dynamics of spin-based systems, computational materials design, active-transport membranes, multifunctional ceramics, and electrets, these programs are:

Spin Interactions and Spin Dynamics in Electronic Nanostructures
Professor Robert Buhrman, Cornell University

The objective of the research is to understand and manipulate the spin interactions and spin dynamics at the nanoscale, and then to apply this understanding to develop a range of spin-based devices. The research program seeks to accomplish the following:

- Develop techniques to observe spin assemblies, working towards the goal of attaining individual spin sensitivity;

- Establish a full understanding and control of magnetic interactions in frustrated spin systems and develop the means to reversibly reorient spins in such systems;

- Develop techniques for controlling dynamic spin phenomena in nanoscale systems, including both isolated nanomagnets and nanomagnetic arrays; and

- Apply this research in the development of several prototype devices including spin-based non-volatile magnetic RAM, a high-frequency mixer, a spin oscillator and an electron quantum-state entangler.

Computationally Engineered Microstructural Complexity in Ferroelectric Systems
Professor Kaushik Bhattacharya, California Institute of Technology

The goal of the program is to extend our ability to computationally treat the complexities found in real materials systems. Specifically, the MURI addresses very fundamental issues related to multi-scale modeling of the microstructure and actuation properties of thin-film ferroelectrics, notably the solid solution system of lead barium titanate (PBT). The end objective is to use a combination of theory and experiment to optimize the design and performance of a PBT thin-film microelectromechanical (MEMS) actuator. An aggressive performance goal of 5% strain has been set for the actuator. The research program includes:

- Multiscale modeling of microstructural evolution and its affect on mechanical behavior;

- Deposition of highly textured PBT thin films on silicon substrates;

- Characterization of domain wall structure and mobility in applied electromechanical fields; and

- Design of a micropump and an array of microactuators using thin-film ferroelectrics.

Flexible Membranes for Active Transport of HCl,
Professor John Cuppoletti, University of Cincinnati

The objective of this MURI is to produce synthetic flexible membranes containing biological transport proteins that can utilize energy for the selective uptake, concentration and release of ions and molecules in an organized manner. The effort includes production of both macroscopic membranes and nanostructures containing transport proteins with vectorial transport function. The research combines both experimental and theoretical studies utilizing a very promising membrane transport system; the fundamental concepts developed from this effort are expected to provide significant insight into many other transport systems. The MURI program may enable novel materials for: fuel cell membranes, reverse osmosis and active filter membranes, drug delivery systems, moisture-removing fabrics, and chemical and biological defense. The research program includes:

- Reconstitution of the gastric HCl secretory apparatus into synthetic flexible membranes in functional form;

- Investigation of the structural determinants of regulatory regions in native and specifically modified or engineered proteins;

- Application of control mechanisms such as pH, ionic conditions, membrane voltage, and intracellular second messengers;

- Identification and engineering, using guidance from computational modeling, of transport systems with the capability to transport other substances; and

- ■ Design of macroscopic and nanoscopic planar and three-dimensional membrane support structures.

Self-Assembly of 3-D Multifunctional Ceramic Composites for Photonics and Sensors
Professor Paul Braun, University of Illinois at Urbana-Champaign

The objective of this MURI is to enable the formation of exquisitely controlled, 3-D structures from colloidal particles, sol-gel precursors, and biological molecules in order to develop the multifunctionality required for a diverse array of optical devices and sensors. Photonic crystal theory, including unique large-scale computational tools for full-vector electromagnetic simulations, will provide the foundation for designing unique and optimized photonic bandgap materials. State-of-the-art computational algorithms and materials science theory will be used to guide the development of the following complementary processing and assembly strategies:

- ■ New colloidal self-assembly routes that combine nanoparticle- and DNA-mediated colloidal assembly with colloidal epitaxy to create colloidal crystals with exact orientation with respect to a substrate and defined crystal symmetries;

- ■ Multi-beam ceramic holography as a route to 3-D nano- and micro- scale periodic ceramics;

- ■ Ceramic/liquid crystal composite optical switches;

- ■ UV and multiphoton patterning of sol-gel ceramic precursors as a route to sub micron engineered ceramic structures; and

- ■ Robotically controlled deposition of ceramic nanoparticle-polymer composites.

Design and Processing of Electret Structures
Professor George Whitesides, Harvard University
Professor Ilhan Aksay, Princeton University

Electrets are materials that store permanent charges or electric dipoles in their structures. These materials are important as sensors, particularly as pressure sensors in electret microphones, and for information storage, such as in holographic memories. They are also important as tools and templates in the guided assembly of molecular-scale structures into larger materials systems. Charge storage capacity and physical properties of the materials available limit applications along these lines. In addition, the exact mechanisms for charge transfer and storage are not particularly well understood. While they likely involve both ionic and electronic contributions, the total charge concentrations are extremely low (10^{-9} molar concentrations are typical). This project will use a multidisciplinary approach to:

- Quantify charge transfer reaction kinetics and determine mechanisms for various polymeric and soft materials;

- Develop mechanism-based models for the transfer and storage of charge in molecular assemblies;

- Develop new charge storage materials using both ionic and electronic charging mechanisms based on designed molecular structures;

- Explore charge transfer in liquids and soft-matter systems and develop techniques for control of electrets in soft systems;

- Identify techniques for the directed assembly of supramolecular systems using electrostatic templating and electrodynamic control.

2**. Defense Experimental Program to Stimulate Competitive Research (DEPSCoR) -** The DEPSCoR program supports single investigator research at universities located in states that have not traditionally been recipients of large amounts of federal research awards. DEPSCoR is designed to improve the capabilities of U.S. institutions of higher education in these states, to conduct research, and to educate scientists and engineers in areas important to the national defense. The one new program awarded in FY04 was:

- Magnetic Composites with Designed and Tunable Permittivity and Permeability for Microwave Applications, Professor John Xiao of the University of Delaware

3. **Historically Black Colleges and Universities/Minority Institutions** - The HBCU/MI program is intended to enhance research capabilities and infrastructure at these institutions and increase the number of under-represented minority graduates in the field of materials science. The four new programs awarded in FY04 were:

- Fabrication and Modeling of Porous NiTi Memory Alloys, Professor Yi-Chao Chen of the University of Houston

- Upgrade of the Electron Microscopy Facilities, Professor John Lee of City College of the City University of New York

- Nanolayers and Nanoparticles of Solid Solution: Theory and Computer Simulation, Professor Alexander Umantsev of Fayetteville State University

- Acquisition of a parallel Beowolf Cluster for Computational Materials Research and Education, Professor Nichloas Kioussis of California State University Northridge

4. **Tribal Colleges and Universities** - The TCU program is intended to enhance the math and science curriculum at these institutions and increase the number of students that

go on to major in math and science. The TCU programs funded by the division during FY04 were:

- Stone Child College Math-Science Instrumentation Project - Douglas Crebs, Stone Child College

- Mandan, Hidatsa, Arikara Nation: Improving Math and Science Using the Tools of Technology - Clarice Baker – Big Back, Fort Berthold Community College

- DoD: Instrumentation Program for Tribal Colleges and Universities - John Runnion, Sinte Gleska University

5. **Defense University Research Instrumentation Program (DURIP)** - The Division awarded four instrumentation grants to universities under the FY04 DURIP program. The objective of this program is to enhance the nation's infrastructure by encouraging the design and fabrication of novel experimental capabilities and the addition of new equipment that directly supports DoD research being conducted at US universities. The new programs awarded in FY04 were:

- Aerodynamic Breakup of Liquid Drops in Supersonic Flows, Professor Theofanis G. Theofanous of the University of California, Santa Barbara

- Spectroscopic Ellipsometer for in-situ and ex-situ Characterization of Ferroelectric Thin Films, Professor Harry A. Atwater of the California Institute of Technology

- Instrumentation for High-Resolution Spectroscopic Cryo-Imaging of Solvated Polymers, Professor Matthew Libera of Stevens Institute of Technology

- Instrumentation of Monochromatic X-ray Side-station for Melt Property Study at X17B2 of the NSLS, Professor Jiuhua Chen of the State University of New York at Stony Brook

6. **Defense Advanced Research Projects Agency (DARPA)** - On behalf of DARPA the Materials Science Division manages programs in the areas such as thermoelectric materials, spin-based electronics, exchange-coupled magnets, tunable optics, tunable RF materials, magnetic resonance force microscopy, amorphous metals, actuator development, soldier locomotion and augmentation, and synthetic multifunctional materials. The nine new programs awarded in FY04 were:

- Meta-Materials Design in a New Dimension, Professor Chunlei Guo, University of Rochester

- Quantum readout and Control of Spins by Ultrasensitive Force Detection, Dr. Daniel Rugar, IBM Research Division and Professor John Sidles of the University of Washington

- Multifunctional Next-Generation Carbon Nanotube Super Fibers, Dr. Jian Chen of Zyvex Corporation

- Simultaneous Multiple Wavelength, Multiple Field of View Imaging System, Professor Paul H. Holloway, of the University of Florida

- Foveated, Wide Field-of-view Imaging Sensor for Missile Warning/Tracking using Adaptive Optics, Professor Shin-Tson Wu of the University of Central Florida

- Resonant Photonic Bandgap Nanostructures, Professor Arthur L. Smirl of the University of Iowa

- Development of Advanced Active Haptic System for Musculoskeleton Interactions, Professor Rahmat A. Shouresbi of the University of Denver

- High Energy Density Nastic Structures Using Biological Transport Mechanisms, Professor Donald Leo of the Virginia Polytechnic Institute and State University

- Reversible Nanoparticle Electronics, Professor Angela M. Belcher of Massachusetts Institute of Technology

7. **Missile Defense Agency (MDA)** - In FY04 the division managed on behalf of MDA two Phase II programs:

- Inspection of Composite Adhesive Bonds with an Electrochemical Sensor - Guy Davis, DACCO SCI, Inc.

- Pulsed Arc Molecular Beam Deposition Tool for High Quality Films and Coatings - Robert DeLeon, AMBP Tech Corp

IV. SCIENTIFIC ACCOMPLISHMENTS

Alloys-by-Design Strategies Using Stochastic Multi-Objective Optimization
Professor George Dulikravich, Department of Mechanical & Materials Engineering, Florida International University

The design of materials is the cornerstone of Materials Engineering. The optimization of materials performance, though, is based on the chain of relating processing to structure to properties and finally to performance. The existing theoretical models that provide these relationships are very complex and generally not amenable to engineering analysis. For this reason, many of the computation-based design of materials efforts are limited to systems where a wealth of experimental data is available to support the calculations. In addition, many of the performance criteria are mutually exclusive. This activity has

taken a completely different approach, treating the design question as a system identification problem. In collaboration with an experimental mechanical metallurgy group in Russia, the project started with a set of experimental performance data, the "knowledge" of data was contained within a trained neural net. A Pareto optimization tool uses this neural net as a data source for determining the optimum alloy, based on the target performance criteria. At this point, the approach is naïve in that it ignores physical metallurgy. The heart of the study is the stochastic optimization, however, which can use any set of captured knowledge. For this reason, a materials developer can merge this optimization technique with other efforts to design alloys based on the fundamental structure-property relationships.
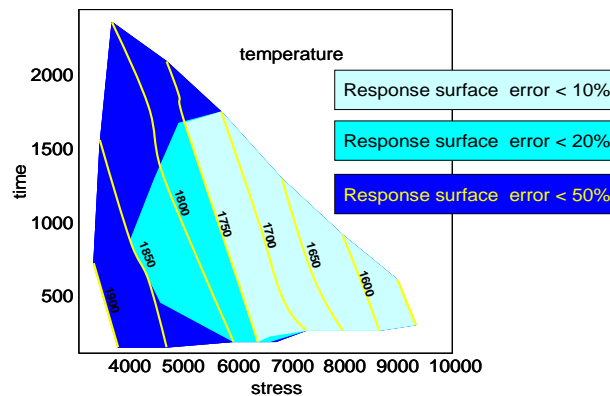
Figure 1. The response surface for various Cr-Ni-Mo steel compositions showing optimum stress vs. time-to-rupture for various service temperatures. The response surface error is an indication of the confidence in the available information.
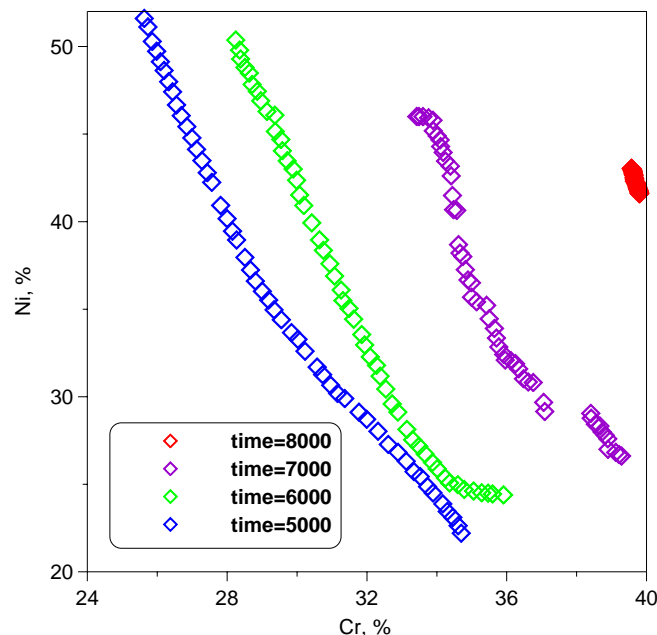
Figure 2. Allowable Ni-Cr steel alloys for service at a stress level of 4 ksi at 1800°F for increasing time.

Structural Amorphous Metallic Foams
Professor William Johnson, California Institute of Technology
Professor David Dunand, Northwestern University
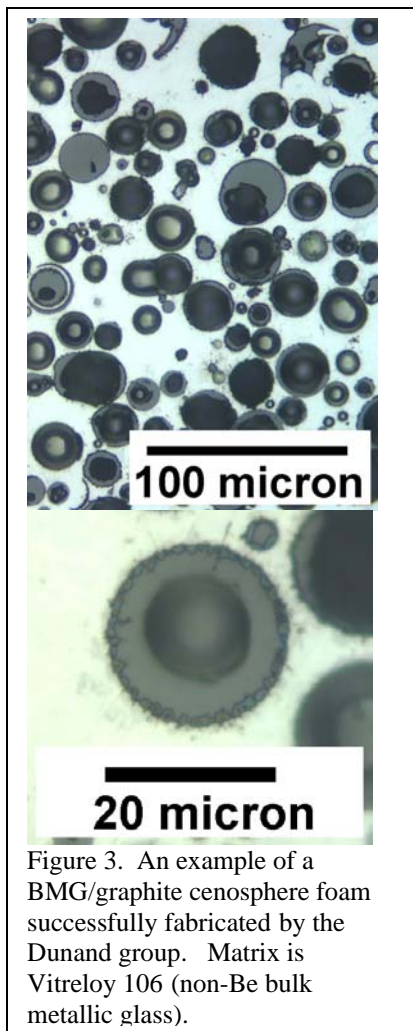
Figure 3. An example of a BMG/graphite cenosphere foam successfully fabricated by the Dunand group. Matrix is Vitreloy 106 (non-Be bulk metallic glass).

Metallic glasses have high specific strengths, which make them attractive for structural applications. The primary deformation mechanism is by shear banding, which is dynamically unstable and leads to catastrophic failure with little overall plastic deformation and low energy dissipation. However, this makes them very brittle and thus poor choices for many structural applications. The group at CalTech has discovered that the shear banding mechanism is highly influenced by boundary effects. In thin sections, easy shear band initiation leads to large deformations by a cascading series of shear bands. This allows the folding and creasing of many foils and ribbons without breaking, while in thick sections they are brittle. To take advantage of this property in thick sections, the answer is foam. By producing foam, all of the metallic glass is located between the foam cells, in thin sections. The high strength of the metallic glass allows the material to maintain high strength, even with densities as low as 50%. The thin sections between the foam cells deform plastically without failure, which provides good ductility. The result is a structural material with relatively low density, high strength, and good fracture toughness and damage tolerance. Current activities are to reduce the cost of producing the foams and to address scale-up issues for industrial scale production.

Surface Behavior of Tackified Adhesives with Aging and its Dependence upon Humidity
Professor Mark D. Foster, University of Akron

The University of Akron group has improved nanoprobe measurements of the effect of humidity on adhesives. By modifying the probe (tip) with a hydrophobic self-assembled monolayer, a force-distance measurement may be used to quantify adhesion at a film surface. The measurement is performed, as shown in figure 1, by moving the probe toward the sample, indenting the sample with the probe slightly, and then removing the probe. During this cycle the force varies with deflection of the cantilever as shown in

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figure 4. In this plot the cantilever deflection has been interpreted as a displacement. The pull-off force, noted in the plot, is the maximum tensile force attained during retraction of the tip.

Figure 5 shows the variation of pull-off force with relative humidity for a test surface for two different tips, one unmodified and the other coated with the hydrophobic monolayer. The pull-off force varies markedly with humidity in the case of the unmodified tip, due to the capillary forces acting on the tip. That is, even though the character of the sample itself does not change with humidity, the apparent adhesiveness of the surface changes just due to capillary forces. This influence is undesirable. However, when the tip is modified, capillary interactions are substantially minimized and the pull-off force remains nearly unchanged with humidity. This sets the stage for improved measurements of adhesive surfaces in humid environments.
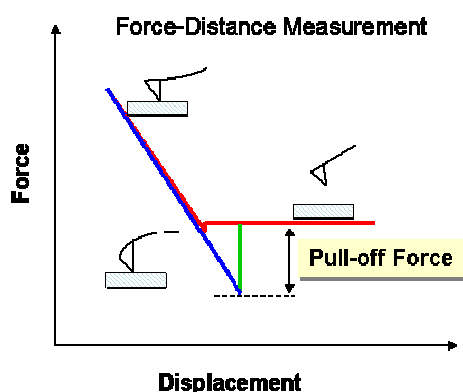
Figure 4
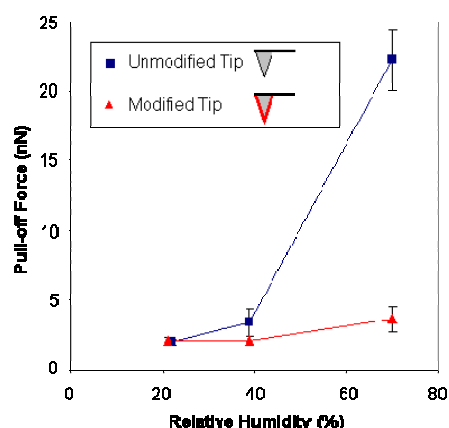
Figure 5

In-situ Nondestructive Atomic Level Characterization of Ferromagnetic Metal/Compound Semiconductor Heterostructures
Christopher J. Palmstrøm, University of Minnesota

< 1 ML ErAs - Er/Ga exchange reaction

The University of Minnesota group has used an in-situ nondestructive atomic level characterization of ferromagnetic metal – compound semiconductor heterostructure growth to define and demonstrate an embedded mode of growth. ErAs films grow on GaAs (100) surfaces by means of this embedded growth mode. The growth is initiated with the nucleation of ErAs islands within the surface of the GaAs substrate due to an exchange reaction between the impinging Er and the Ga bonded in GaAs. The Er displaces the Ga to the surface and bonds with As within the surface region. The displaced Ga is forced to the surface where it bonds with surface As and reforms GaAs on regions of the surface unoccupied by the ErAs islands. As shown schematically, once the ErAs islands reach 3-4 ML in height, the islands act as a diffusion barrier to Er, Ga, and As and limit further growth
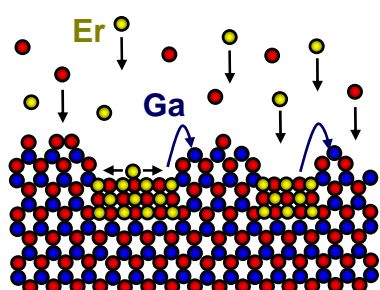
1 to 4 ML ErAs - ErAs islands form diffusion barrier limiting vertical growth promoting lateral growth

into the substrate; thereby promoting lateral growth of the islands. With continued growth, the 3-4 ML islands coalesce and form a continuous uniform layer on the GaAs. Subsequently, further growth results in layer-by-layer growth of the ErAs films. The research has also demonstrated that in spite of strain effects, $Sc_{1-y}Er_yAs$/GaAs(100) films under tensile (ScAs), compressive (ErAs), or even under virtually no

< 4 ML ErAs - ErAs islands coalesce forming a uniform and continuous film

ErA
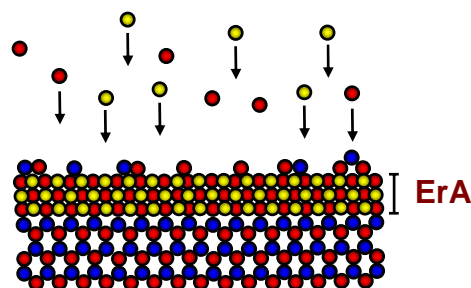
strain ($Sc_{0.3}Er_{0.7}As$), will grow via the embedded growth mode; indicating that strain is not a critical factor in determining the growth mode. However, strain and growth temperature do influence the size and distribution of islands nucleated during growth.

Flux-Pinned Superconducting Magnets
R. Weinstein, University of Houston

Investigators at the University of Houston have investigated the role of the structure of ion-induced damage tracks as pinning sites for fluxoids (quantized magnetic flux lines) in 2 cm diameter by 8 mm thick discs of type II high-temperature superconducting oxides. The pinning of the fluxoids to the nonconducting damage tracks is important because it reduces dissipative electric fields that degrade critical currents (J_C) and maximizes magnetic field trapping. High ion energy transfer rates (>3.5 keV/A) result in columnar damage tracks that run through the thickness of the material. It has always been assumed that the optimal pinning defects will be those of a continuous nature, since the entire length of the fluxoid can lie within the columnar defect. However, a measure of the pinning efficiency vs. ion energy actually revealed that the best results were achieved in samples where lower energy transfer rates were used. These experiments generated discontinuous tracks, but also resulted in much less overall damage to the material per ion. Thus, greater overall ion fluence (higher defect densities) could be introduced before approaching the critical minimum volume of undamaged superconducting phase needed to support its critical current (J_C). The assumption is that the fluxoid can be pinned just as well (pinned along 99% of its original length) in these discontinuous columnar systems by crossing over from one damage track to another neighboring track as it meanders

across the sample thickness. The gains were quite significant – the pinning effectiveness could be more than five times greater than that obtained with continuous pinning defects.

Single Spin Detection Using Magnetic Resonance Force Microscopy
D. Rugar at IBM Research Division, Almaden Research Center,

Under a DARPA-funded program managed by ARO, IBM researchers have reached a historic milestone. They have demonstrated that they can detect the presence of a single electron spin using magnetic resonance force microscopy (MRFM). MRFM is a cantilever-based technique; where the force between a ferromagnetic tip and the spins in the sample are measured. The present experiments were conducted on vitreous silica sample, which had been irradiated with Co^{60} gamma rays to produce a very low concentration of E' centers, silicon dangling bonds composed of unpaired electron spins. The detection of a single isolated electronic spin highlights the level of improvement in instrument sensitivity that has occurred the past decade. Over 7 orders of magnitude improvement in instrument sensitivity have been demonstrated since the original MRFM experiment was conducted twelve years ago.   Some of the key innovations that have led to this advance include: (1) ultrasensitive mass-loaded cantilevers that can detect attonewton forces while suppressing thermal vibrations in higher order modes, (2) magnetic tips that can generate >5 Gauss/nanometer field gradient, (3) an efficient superconducting resonator that can produce 4 gauss of microwave magnetic field with less than 1 mW of power dissipation, (4) advanced spin manipulation techniques that allow coherent spin manipulations for up to 3 seconds, and (5) an apparatus that reliably works at cryogenic temperatures, in this case 1.6 K. The figure 6 shows the MRFM spin signal detected as the sample was scanned laterally in the x direction over a single E' center (a single unpaired electron spin). The ultimate goal for the program is to continue to improve on device sensitivity to achieve single nuclear spin detection and ultimately to provide the capability for conducting single spin NMR imaging.
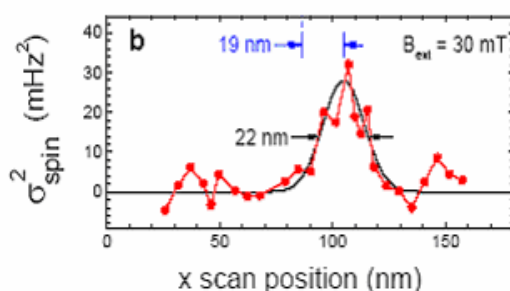
Figure 6. MRFM spin signal

Fabrication of Unique Large-Strain Magnetic Shape Memory Alloys
Ibrahim Karaman, Texas A&M University

The magnetic shape memory phenomenon offers the basis for a unique class of shape memory alloy materials with extraordinary potential for large force, large strain, and high frequency actuator materials. While existing magnetic shape memory alloys are limited by a minimal shape memory effect, researchers at Texas A&M University have

developed advanced models that enabled the design and fabrication of unique single crystal alloys exhibiting strains as high as 10% in tension. The researchers developed a thermodynamically sound model that accounts for hysteretic effects and couples temperature, stress and magnetic field effects; furthermore, careful magneto-thermo-mechanical characterization studies on existing NiMnGa and new CoNiAl alloys identified certain microstructural and magnetic requirements necessary to obtain large magnetic field induced strain such as twin boundary mobility, high strength against dislocation formation, low volume change upon transformation, high saturation magnetization and magnetocrystalline anisotropy energy. Compositions of CoNiAl, CoNiGa and FeNiGa systems were then modified to satisfy these requirements. In newly developed CoNiAl and CoNiGa alloy single crystals, transformation and pseudoelastic strains were as high as 4.2 % under compression and 10% in tension. The tension/compression asymmetry is attributed to the ease of detwinning under tension. A large difference between stresses required for martensitic transformation and for dislocation slip was evident in single crystals. Utilizing the new MTM set-up, the relationship between coupled magnetic/stress field and martensite reorientation and also hysteresis effects were revealed and possible mechanism were suggested considering the competing effects of elastic energy storage and dissipation. A constitutive model based on Gibbs free energy expression which includes magnetic energy terms was developed. In this model, dissipative effects introduced through internal state variables, which are physically motivated by magnetic and crystallographic microstructure.
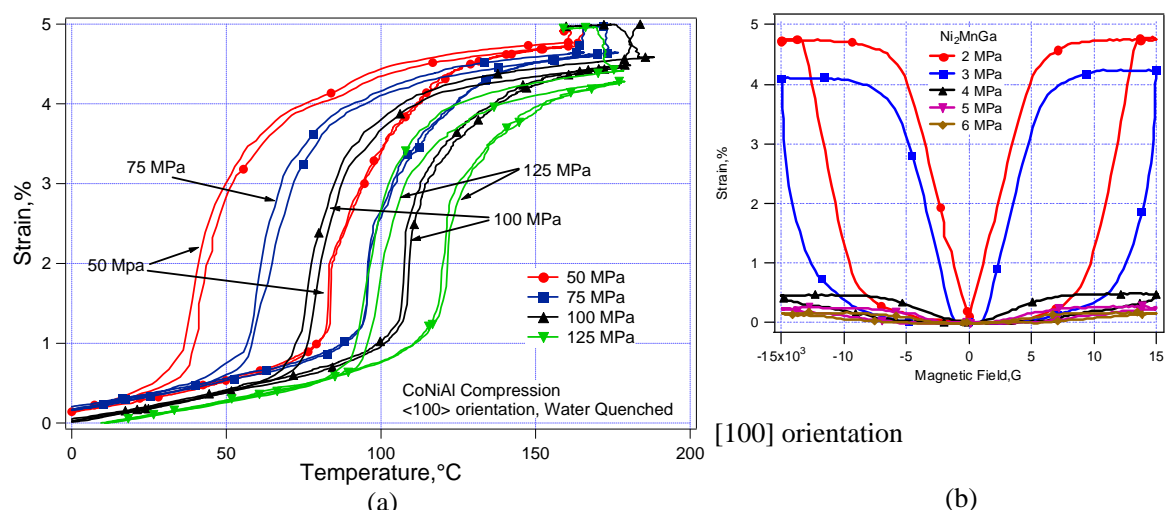
Figure 7. (a) Strain vs. temperature response of a new CoNiAl alloy under different constant stress levels showing more than 4% shape memory strain, shrinkage in hysteresis as a function of stress and complete recoverability. (b) Strain vs. magnetic field response of Ni_2MnGa demonstrating very large MFIS (more than 4.5%), the coupled effect of magnetic/stress fields on strain level, hysteresis, the field at which reorientation starts and stored energy are notable.

Demonstration of Hall-Petch Breakdown at Nanoscale

Christopher A. Schuh, Massachusetts Institute of Technology

It has been widely speculated that the normal Hall-Petch scaling law that relates an alloy's strength or hardness to its grain size must fail when the grain size of a metal reaches the finest nanostructural scales (< 10 nm). This "Hall-Petch breakdown" has been controversial due to a scarcity of sound experimental data, but researchers at MIT have recently developed electrodeposition methods to produce high-quality nanocrystalline metals in the Ni-W system, with grain sizes ranging from ~70 nm all the way down to the amorphous limit (~ 1 nm). The hardness trend obtained from these specimens is shown in the Hall-Petch plot below, and constitutes one of the clearest demonstrations of a Hall-Petch breakdown to date. To understand the physical origins of the Hall-Petch breakdown, these researchers have used atomistic simulations to directly observe the mechanisms of deformation in nanostructured metals. In particular, the simulations reveal the commonalities and differences between fully disordered, amorphous metals (with grain size ~0-1 nm) and nanocrystalline metals with grain sizes below the Hall-Petch breakdown. Neither of these materials is found to exhibit dislocation activity, instead deforming via small avalanches of shear distortion, called 'shear transformation zones.' In amorphous metals these zones are located throughout the structure, while in the nanocrystalline metals they are confined to the grain boundaries. The dominance of this deformation mechanism in both amorphous and nanocrystalline metals leads to unusual macroscopic behavior. For example, the simulated stress-strain curves shown below at the right illustrate a hitherto unexpected behavior of nanocrystalline metals: they are stronger in tensile states of loading than they are in compression.
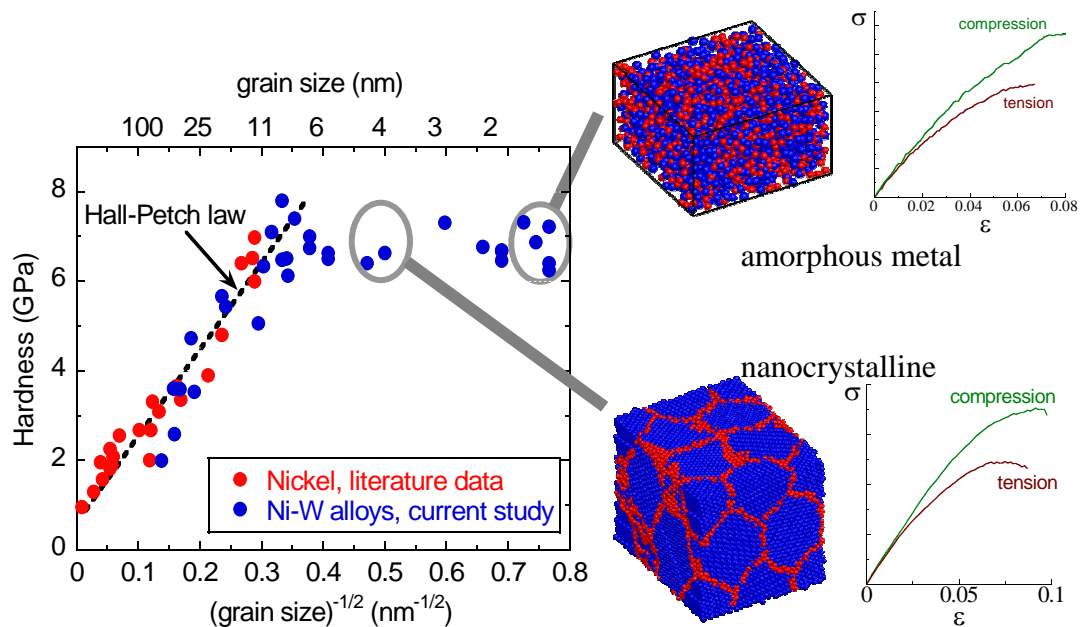
Figure 8. Hall-Petch plot.

V. TECHNOLOGY TRANSFER

Affordable Hybrid Composites for Next Generation Gun Systems
Fred Lauten, Triton Systems

A major factor in the weight of a combat vehicle is the weight of the gun tube. The weight of a 155mm gun tube can be as much as 2 tons. Carried in cantilever, the required supporting structure to steady and point the gun is significantly greater. In addition, the increased demands for lethality have driven designers to use higher energy propellants, which increase the wear and erosion rates of the tubes dramatically. The long term solution to both problems is the development of a lightweight, high strength and hardness material capable of withstanding high temperatures and shock. This group has developed a functionally graded material consisting of a ceramic-matrix composite core to withstand the high heat wear. An aluminum-matrix composite surrounds the core to provide mechanical integrity of the tube. Triton produced prototype tubes sections successfully tested them in the laboratory environment. The Army Research Laboratory has chosen the material as the primary liner for their lightweight mortar programme, and the Naval Surface Warfare Centre is adopted the material for their advanced 155mm shipboard gun system.
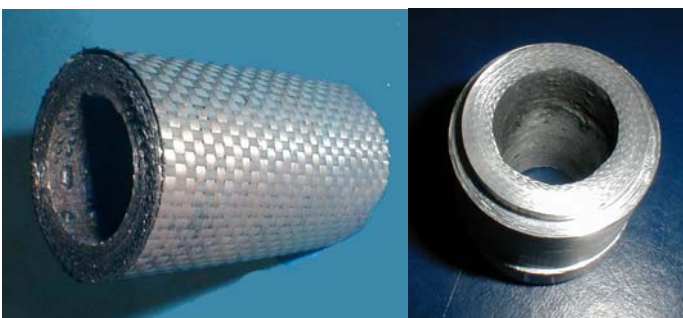
Figure 9. Chemical Vapour Infiltrated Ceramic-matrix composite core (left) wrapped with Nextel fibre in preparation for aluminum infiltration. Tube section after pressure infiltration casting (right).

Computationally Engineered Microstructural Complexity in Ferroelectric Systems

The researchers from the California Institute of Technology involved in "Multiscale modeling and process optimization for engineered microstructural complexity" have had multiple transition interactions with the Army Research Laboratory over the past year. For example, Dr. G. Ravichandran of California Institute of Technology and Dr. Madan Dubey of Army Research Laboratory organized a joint Caltech – DoD workshop at the Army Research Laboratory, Adelphi MD. The workshop featured seven speakers from Caltech and five speakers from ARL and NRL, poster sessions by both ARL and Caltech scientists, a visit to ARL facilities and a brainstorming session to explore potential collaboration opportunities. Numerous areas for potential collaboration emerged and are being pursued. For example, Jennifer Rugolvsky, a graduate student in the Atwater group in Caltech has been working at ARL, Adelphi conducting microactuator synthesis with Dr. Brett Piekarski. Another example, Dr. Melanie Cole, Army Research Laboratory, Aberdeen, is pursuing a collaboration which will transition a Caltech CVD reactor design (Boyd, Goodwin) to the ARL active materials group. This transition will

also include the modeling and deposition research efforts of functionally graded BST (Atwater, Boyd, Bhattacharya).

Custom-Designed High Performance Steels

Researchers at Northwestern University, with the support of the U.S. Army Research Office, have developed a robust multi-scale approach to materials design integrating simulations from the full range of relevant length and time scales, physics, and chemistry to enable custom design of advanced steels. The introduction and commercialization of this new class of "Ferrium" steels has led to the formation of QuesTek Innovations LLC. Most recently, these advanced steels, which were designed to have extremely high strengths and toughness for wear resistance, have been demonstrated to provide unprecedented performance in the automotive racing industry. The steels enabled a novel narrow gear design that was incorporated into a vehicle competing in a recent NASCAR race, as well as an advanced ring and pinion design that was integrated into a vehicle competing in a recent SCORE International off-road race. Both of these designs are now being produced commercially.

Compact Motor Designs based on Frequency Rectification Commercialized

In the late 1990's researchers headed by Professor Gregory Carmen at UCLA demonstrated the design of compact actuators based on the concept of frequency rectification, where actuator work is accumulated over time through the integration over many small steps. The research capitalized on recent advances in microelectromechanical (MEMS) machining and active materials (e.g., piezoelectric actuator materials) to conduct pioneering studies on frequency rectification. These ultimately led to the demonstration of a compact inch-worm type actuator that delivered extremely high power densities, values on the order of 20,000 W/kg. Typical electromagnetic motors are capable of providing power output per unit mass values that peak at only about 1000 W/kg, and drop off precipitously as their volume decreases, rendering them useless in smaller-scale applications. Thus, the research provided a revolutionary paradigm shift for the industry. Based on these and other advances EXFO is now producing a commercially available version of the original UCLA actuator. A picture of the available device is shown in the figure 10a. This novel device is capable of delivering centimeter strokes with nanometer precision and forces approaching 200 N. Based on similar frequency rectification concepts, several other concepts have been developed. One notable approach couples hydraulics with micro-machined valves to again realize frequency rectification. A commercially available motor of this type is produced by Kinetic Ceramics and is shown in the figure 10b. This particular motor produces force outputs exceeding 1000 N with flow rates exceeding 25 cc/sec. Finally, medical researchers are seeking even smaller versions of these motors that could be used as embedded drug delivery systems. Several companies including Medtronic are actively pursuing the development of system designs for such applications.

(a) EXFO Actuator

(b) Kinetic Ceramics Actuator
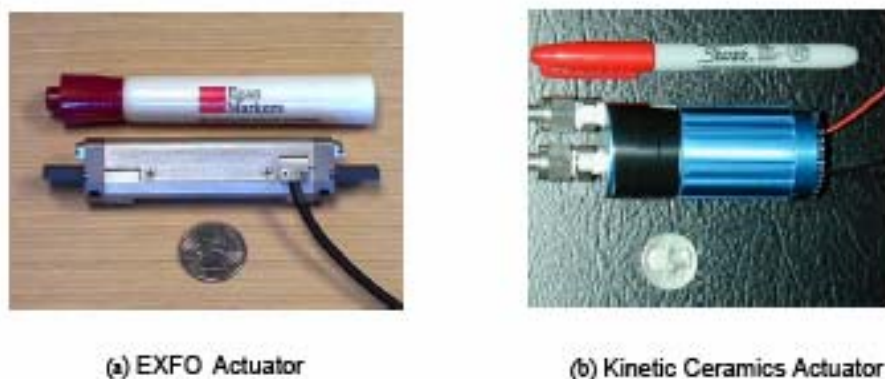
Figure 10. Compact Motor Devices

Workshops and Conferences

During the past year, the Materials Science Division has been involved in organizing the following program reviews, workshops and conferences hosting Army Research Office (ARO) contractors, Army scientists, other U.S. Department of Defense (DoD) scientists, and scientists from the United States and allied nations:

- 2004 Physical Metallurgy Gordon Conference, Property Prediction: The Challenge of Scales, Plymouth, New Hampshire

- Physics and Chemistry of Semiconductor Interfaces, Kailua-Kona Hawaii

- Symposia on Biophysical and Biochemical Properties of Ion Channel Epithelia, Telluride, Colorado

- ARO/GaTech Workshop on Inverse Techniques in Materials Design, Professor Hamid Garmestani, Georgia Institute of Technology

- Materials Research Society Fall Conference, Boston, MA

- NRL Workshop on Functional Electronic Materials – Key to New Science and Technology, in Washington, DC

- 27th Annual International Conference on Advanced Ceramics and Composites, in Cocoa Beach, Florida

- Review Meeting for the Institute for Soldier Nanotechnologies, Boston, MA

- Army Laboratory - ARO Principal Investigator Interactions

During the past year, Materials Science Division researchers and staff have interacted with Army and other DoD scientists through visits, seminars, and discussions at their laboratories in order to bring significant results of ARO-sponsored programs to the attention of Army and other DoD scientists.

VI. DIVISION STAFF

Dr. Douglas Kiserow
Acting Director, Physical Sciences Directorate

Dr. John T. Prater
Associate Director, Materials Science Division
Branch Chief, Physical Behavior of Materials Program

Dr. William V. Lampert
Branch Chief, Materials Reliability Program

Dr. William M. Mullins
Branch Chief, Synthesis and Processing Program

Dr. David M. Stepp
Branch Chief, Mechanical Behavior of Materials Program

Dr. Scott Wolter
Intergovernmental Personnel Act, Special Projects

Danell Diggs
Administrative Support Assistant

I. PROGRAM OBJECTIVES

The contributions of the mathematical sciences have an impact on a wide range of Army needs. The objective of the Mathematical Sciences research programs at the U.S. Army Research Office is to respond to requirements for enhanced capabilities of the Army in the twenty-first century in materials, information, systems, testing, evaluation, acquisition, training, and logistics. Mathematics plays an essential role in measuring, modeling, analysis, and control of complex phenomena and in systems of critical interest to the Army.

With the advent of high performance computing, the mathematical sciences have become an integral part of every scientific and engineering discipline. Computing now complements analysis and experiments as part of a triad that is increasingly successful in understanding physical, biological, and behavioral phenomena. High-performance computing and advanced distributed simulation have become enabling tools for the Army of the future. Real-time acquisition, representation, reduction, and distribution of vast amounts of battlefield information are key ingredients of the digital battlefield. Management of modern information-dominated battlefields provides significant motivation for fundamental research in the design and development of intelligent and cooperative systems.

The major long-term technical objectives of the Mathematical Sciences Division are to:

- Develop new mathematical theories, algorithms, and methods for measuring, modeling, analysis, design, and control of physical processes, and complex systems. These include advanced materials, electromechanical structures and platforms, optical systems, neural dynamics, and physiological processes;

- Develop computing as an enabling tool that complements theory and experimentation for scientific discovery and engineering design and implementation. This includes domain-specific algorithms, implementation environments, evaluation of advanced computing systems, process and large scale simulation, graphics, and visualization;

- Advance the foundations of future intelligent systems by fostering progress in mathematics related to information processing. This includes analysis, control, knowledge acquisition and data representation.

II. RESEARCH PROGRAM

A. General Information

The Mathematical Sciences Division seeks to create coherent mathematical research foci that are, on the one hand, responsive to the changing needs of the Army and, on the other

hand, do not fluctuate too rapidly for the basic research community to recognize and contribute. Research supported by the Division falls into six areas:

- Probability and Statistics;
- Discrete Mathematics and Computer Science;
- Computational Mathematics;
- Modeling of Complex Systems;
- Modeling, Simulation, and Related Mathematics; and Cooperative Systems.

Each of these areas is represented by a program, which typically has two to four foci. Three crosscutting themes, which support areas of Army interest, are: (i) analysis of complex systems, (ii) mathematics of phenomena and (iii) mathematics for modeling, computing, and simulating. Each of the programs of the Division is coordinated with related programs in other Department of Defense (DoD) and Federal agencies. Through this coordination, the Division leverages support of wider efforts in areas of common interest and achieves agreement on areas in which one agency should be the lead agency with primary funding responsibility. This programmatic coordination results in more efficient use of Army and Federal resources.

Core funding for research activities supported by the Division comes from the Army. The Division aggressively leverages additional resources, primarily from the Director, Defense Research and Engineering, [University Research Initiative Programs (URI)], the Ballistic Missile Defense Organization (BMDO), and the Defense Advanced Research Projects Agency (DARPA).

B. Thrusts and Trends/Workpackages

PROBABILITY AND STATISTICS

The Probability and Statistics program supports research in stochastic analysis, applied probability, and statistics in response to the Army's need for decision making under uncertainty and for the test and evaluation of systems in development.

Stochastic Analysis and Applied Probability - Many Army research and development programs are directed toward system design, development, testing, and evaluation problems which depend on the modeling and analysis of stochastic dynamical systems. Such problems generate a need for research in stochastic processes and random fields, or stochastic differential equations. Special emphasis is placed on methods for analyzing data obtained from phenomena modeled by such processes and numerical methods for solving stochastic partial differential equations. The development of useful algorithms in the field of image analysis for ATR (Automatic/Aided Target Recognition) is an especially important issue for the Army. There is a strong need to develop a rigorous model-based framework for ATR utilizing pattern theory, random fields, and Markov Chain Monte Carlo techniques. The Army also has a vital interest in resource management and optimization in very large networks, especially communication networks with stochastic components. Other research areas of importance to the Army in

probability and its applications include interacting particle systems, probabilistic algorithms, stochastic control, stochastic optimization, nonlinear filtering for stochastic partial and functional differential equation, and simulation methodologies.

Statistical Methods - The state-of-the-art in statistical methods is well adapted to elicit information from medium-size data sets collected under reasonable conditions from moderately well understood statistical distributions. However, Army analysts frequently have very large or very small data sets sampled from nonstandard, poorly understood distributions. The two situations lead to very different statistical problems. The information available in large multidimensional data sets is frequently obscured, which suggests the application of data mining methods. Large data sets may occur in a stream, that is, they may be produced quickly and continually, so that new data compression methods are required to exact and update the relevant information for the decision-maker. The quality of the data is often varied because environmental factors are not under the control of the individuals and systems that collect the data. The advantages associated with quantity then are superseded by the need for improved data quality. In many testing situations, only small amounts of data are available due to cost, time, and safety constraints. The problems to be studied are sometimes vaguely formulated and appropriate models are not developed before acquiring the data. Close collaboration with scientists who work in the field of application, is required to develop new methodologies for addressing the problem of extracting information from meager samples. To extract more information from less data, improved methods for combining information from disparate tests may be needed. Reliability and life length methodologies are needed for analyzing mechanical and electrical systems, especially those with extremely low failure rates.

DISCRETE MATHEMATICS AND COMPUTER SCIENCE

Discrete mathematics and computer science play key roles in the effective implementation of the digital battlefield which is a major component of FCS (Future Combat Systems). Research in these areas is also crucial in fighting and winning the information warfare of the future and determining and analyzing alternatives for battle strategies. This program supports the three strategic themes of the Mathematics division by enhancing the understanding of discrete phenomena and digital information environments (complex systems), providing rigorous algorithmic foundations and better modeling tools, as well as advancing the underpinning mathematics and enabling technology for distributed interactive simulation for both physically based and non-physically based models. (Training simulations would be an example of a non-physically based model). The major thrusts in this program are targeted to address the Army's, especially with regards to FCS, and DoD's interests in training and war-gaming, reconnaissance and surveillance, battlefield management, information warfare, terrain dominance, manufacturing, telemedicine, design, validation and performance evaluation for material/system acquisition, virtual prototyping, field testing, and logistics support.

Discrete Mathematics - The foci of the research in discrete mathematics are the development and analysis of solution procedures for discrete problems in computational

geometry, computational algebra, mixed symbolic-numerical computing and robust geometric computing, logic, network flows, graph theory and combinatorics. Research in these areas offers powerful tools for a number of applications related to FCS (Future Combat Systems) including robotics, autonomous navigation, battle management, C^3, virtual prototyping and manufacturing, and computational modeling and simulation. In addition this sub-area supports Army interests in soldier systems and vulnerability and lethality analysis which may require geometric and solid modeling, interactive graphics and 3D visualization tools, as well as physically based modeling. Some of these efforts overlap with those in the *Computational Mathematics* and the *Modeling, Simulation & Related Mathematics* programs.

Computer Science - Advances in computer hardware and architecture continue to outpace development in algorithms and software for the solution of applied physical and biological problems, such as terrain modeling and human dynamics. Many computationally intensive problems, such as those encountered in advanced distributed simulation, require information processing and data manipulation. Of interest is research on fundamental issues in parallel computing and algorithms, distributed computation, models and algorithms for the control of heterogeneous concurrent computing, I/O communication and large-scale memory management, human-computer interface, etc. Exploring fundamental techniques that advance computational algorithms and analytical tools to enable battlefield digitization is a research focus of great strategic importance to FCS and hence this sub-area. Some of these efforts overlap with those in the *Computational Mathematics* and the *Probability and Statistics* programs.

COMPUTATIONAL MATHEMATICS

The Computational Mathematics program supports the three strategic themes of the Mathematics division by developing innovative, efficient and accurate numerical methods, optimization techniques and scalable scientific software tools. Such methods and tools assure that mathematical models can be translated into realistic simulations. The quantitative predictions of most modern theories can only be derived from extensive computations. As Army problems become more complex, new and better approaches will be needed to understand, design and optimize their solutions. The overall focus of the Computational Mathematics program is on algorithmic problems which arise as we attempt new applications and on how common features of these problems can lead to general solution methods for classes of problems.

Numerical Methods - The primary interest in this subarea is on finding solutions to algorithmic problems associated with new applications and currently intractable computational problems. Among the barriers, which need to be addressed, are interacting subsystems, multiple scales and the effects of uncertainty. Different parts of a numerical simulation may be described by different mathematical models at different scales. New methods are needed to couple different types of models, simplify the complexity of systems and accurately compute small-scale effects in a large scale simulation without brute force. Algorithms need to be designed to take advantage of the mathematical structure of the application. Analysis is needed to determine structure, assess the

performance of the algorithms and drive adaptivity. Design, control and optimization require that simulations be performed many times. To accelerate such repeated simulations, reduced order models and fast algorithms in core areas such as linear algebra, ordinary differential equations and partial differential equations become important. Fast algorithms are also important for solution of global models such as those described by integral equations. Considerable progress has been made on the numerical treatment of interfaces, singularities and difficult boundary conditions but new applications may create new types of interfaces. Uncertainty arises in models, parameters and interactions among components. Systematic methods are needed to evaluate and quantify the effects of these and other sources of uncertainty. This appears to be an open area at this time.

Optimization - As computing power increases, optimization will replace trial and error as the approach of choice for the solution of DoD problems. Problems of interest to DoD in science, engineering and operations are usually large, nonlinear and global with many local minima. A single problem may contain continuous, discrete and integer variables. The primary interest of this subarea is in mathematically rigorous methods for solving such problems. The emphasis is on methods rather than specific applications. Mathematical analysis is essential to this effort.

Software Tools - As numerical computations become larger and more complex, non-numerical issues become important. Computer architectures vary. We have complex memory hierarchies, distributed data and networks with different bandwidths. Mathematical tools are needed to map algorithms to architectures with minimal input from programmers and users. Huge data sets are ubiquitous. Tools are needed to extract useful information from such data sets and to present results in ways that are easily understood. Progress has been made in grid generation, adaptivity and load balancing but new applications may generate new problems. Some tools have been developed but are not widely used. Some effort is needed to determine why this is so and how such tools could be made more useful for programmers and users. The efforts in this subarea overlap with those in the Discrete Mathematics and Computer Science program.

MODELING OF COMPLEX SYSTEMS

The research supported by the Modeling of Complex Systems Program is fundamental mathematics-oriented research with the objectives of developing quantitative models of complex systems/phenomena and of developing new metrics for these models. The Modeling of Complex Systems Program seeks to achieve a balance between research in physics-based areas and research in information-based areas. Much of the modeling and analysis supported by the program involves new, nontraditional metrics (function spaces). The basic research carried out by the Modeling of Complex Systems Program contributes to the Future Force Technologies C4ISR (Command, Control, Communication, Computers, Information, Surveillance and Reconnaissance), lethality, survivability and mobility and to the Future Combat Systems characteristics comprehensive situational awareness, networked fires - extended range lethality, survival of first engagement, manned/unmanned integration, C-130-like transportation and reduced logistics.

The complex systems of interest to the Modeling of Complex Systems Program include: (1) physical systems, (2) abstract systems in information theory and networks and (3) hybrid systems (physics-based system coupled with information-based superstructure) in the following areas:

- Advanced Complex Materials for Structures, Armor and Sensors
- Inverse Scattering in Complex Media
- Modeling of Multiscale Objects and Functions
- Nonlinear Dynamics for Communication
- Data Fusion in Complex Networks
- Dynamics of Distributed Networks of Embedded Sensors and Actuators
- Additional Areas of Opportunity

Complete and consistent mathematical frameworks for the modeling effort are the preferred context for the research, but research that does not take place in such frameworks can be considered if the systems are so complex that the frameworks are not feasible. Metrics are part of the mathematical framework and are of great interest. Traditional metrics, when they exist, often do not measure the characteristics in which observers in general and the Army in particular are interested. For many complex systems, new metrics need to be developed at the same time as new models. Just as is the case for the modeling effort, these metrics should preferably be in a complete mathematical framework

Advanced Complex Materials for Structures, Armor and Sensors: The Modeling of Complex Systems Program supports research oriented toward optimizing properties or performance characteristics of highly nonlinear materials, including advanced composites for structures and armor and smart materials for sensors. Advanced composites are challenging to analyze and design because of the presence of many interacting length scales. Smart materials, the functional ingredients of actuators, sensors and transducers, have a load- or field-dependent (crystal or other) structure and may undergo phase transformation when mechanical, thermal, electrical or magnetic forces change. Advanced composites and smart materials are typically highly nonlinear. In seeking to understand the relationship between the microscopic and macroscopic length scales of these materials, fundamental issues in nonlinear modeling arise. Developing models for meso and macro behavior of materials that are based on first/basic principles but do not have inordinate complexity is of great importance. Light-weight, high-strength structural components, including advanced composites, contribute to attaining mobility and protection requirements for U.S. forces (as well as to the fuel efficiency and safety of the U.S. automobile fleet).

Inverse Scattering in Complex Media: Inverse scattering is of interest to the Army for detection and identification of landmines and unexploded ordnance with low false alarm rates. This is an area involving the interaction between the propagation of various types of waves in cluttered soils and the inverse problem of detecting location, shape and material properties of solid objects having various waveform signatures. Currently available techniques often have high false alarm rates, which impedes mine clearance.

Additional Army interests include electromagnetic sensing through cluttered battlefield atmospheres, including smoke, fog, flames, etc. Application of inverse scattering techniques for stand-off detection of chemical and biological agents is of potential interest.

Modeling of Multiscale Objects and Functions: Representation of complex, multiscale/mulitresolution geometric objects and of complicated, often high-dimensional abstract phenomena and functions is fundamental for Army, DoD and civilian needs in modeling of terrain, geophysical features, biological objects (including humans and their clothing), computational learning and many other situations. Real-time visualization of huge terrain databases with glitch-free zoom-in/out cannot be achieved with current techniques. Progress in automatic target recognition, robotic vision, representation/ compression of data in general and many other areas depends on development of data compression at ratios and with accuracy that exceed what is currently known. To achieve such compression, new types of approximation theory appropriate for complicated multiscale/multiresolution surfaces and phenomena need to be developed. In these cases, the objects/functions being approximated are not consistent with the assumptions of classical approximation theory. Approximation theory research that results in highly compressed, loss-free or minimally lossy representation is of particular interest. Approximation theory for information flow and other abstract items in large communication and computer networks is an area of interest.

Nonlinear Dynamics for Communication: Enhanced capability in digital communication is recognized as a pivotal element in a modern economy and in national security. At present, digital communication is carried out mainly by linear devices, that is, by transmitters and receivers operating in the so-called linear regime. The option of creating digital communication systems based on transmitters and receivers operating in the nonlinear regime is of considerable interest. One type of nonlinear behavior on which these transmitters, receivers and codes can be based is chaos, that is, the deterministic but complicated behavior of physical systems in which arbitrarily small changes in the input produce large changes in the output. The potential advantages of nonlinear digital communication devices include increased power and bandwidth efficiency, light weight, compactness, increased information-bearing capacity, greater number of channels, low-cost manufacturing, low probability of interception (LPI) and low probability of detection (LPD). The Modeling of Complex Systems Program supports modeling for new, nonlinear transmitters, receivers and codes. Research in controlling chaos, which is inherently unstable, in ways suitable for these devices and codes is important. Investigation of the information theoretic and symbolic dynamic properties of the signals produced (for example, size of alphabets, grammatical constraints on symbol sequences and entropies) is of interest.

Data Fusion in Complex Networks: Enhanced capability in distributed sensing by organized or self-organizing networks of large numbers of geographically dispersed sensors, often microsensors, of various modalities (acoustic, infrared, magnetic, electric-field, etc.) is increasingly recognized as a pivotal element in the ability of defense forces to accomplish their mission. Such networks are a potential replacement for landmine

fields. Over the past generation, great progress has been made in research and development of low-cost sensing devices. However, when networks contain large numbers of sensing devices, issues of information flow and information processing are a challenge for which basic principles remain to be created. Such basic questions as how to measure "goodness" or optimality are still open. The Modeling of Complex Systems Program supports research on information flow and information processing in large, dynamic networks of sensors, primarily microsensors with limited capabilities and power. Development of metrics, preferably based on first principles rather than ad hoc, for measuring goodness is a topic of concern. Developing models (most likely nonlinear rather than linear) for linkage of scales in the information processing system for large networks is of interest. Research that leads to improved information processing under strong constraints on power and communication bandwidth is of particular interest.

Dynamics of Distributed Networks of Embedded Sensors and Actuators: The past twenty years has seen the convergence of communication and computation. This period has also seen the proliferation of embedded integrated-circuit devices, the growth rate of which has been higher than that of personal computers. Low-cost wireless networking, which is now becoming common, may be the catalyst that will lead to networking of embedded devices in Army and DoD sensing and weap on platforms, vehicles, soldiers and command and control organizations. The analysis and design of networks of embedded sensors and actuators will involve modeling at much deeper levels than that of bit flow. This design and analysis requires a solid mathematical foundation focused on issues of stability, robustness and performance not merely of the sensors and actuators but also of the systems in which they are embedded.

Additional Areas of Opportunity: The Modeling of Complex Systems Program supports research in many areas of nonlinear modeling for which few basic principles are currently known, including human behavior and decision making, speech recognition at very low signal-to-noise/signal-to-clutter ratios, information flow in large communication and computer networks and network tomography.

MODELING, SIMULATION AND RELATED MATHEMATICS

This program seeks to maximize the combined power of mathematics and computer science for current challenging problems pertaining to automation, robotics, modeling and simulation. The program is especially aimed at research areas in which models are not known or are too complicated or too massive for direct solutions. Typical problem areas in this program include the following:

1. To develop the mathematical foundations for modeling and simulation of physical phenomena related to robotics and automation. Problem areas include issues of sensing, materials modeling, nonlinear dynamics, etc. Both stochastic and deterministic methods will be considered.
2. To develop rigorous methods for information and data processing related to intelligent systems and decision making.

3. To develop fast data and information fusion methods for battlefield decision situations.
4. To develop innovative methods in high performance computing, large data set applications, and information management related to large-scale simulation problems.
5. To orchestrate the research programs in all of the other programs in the Division and seek for opportunistically close scientific connections among them in working towards achieving the above stated objective.

Results from this program will impact on faster, more efficient and more secured means for information processing systems including wireless communication systems, command-and-control, combat modeling and other battlespace simulations, automation, robotics, complex networks, and logistic systems.

COOPERATIVE SYSTEMS

The objective of this program is to study and take advantage of the combined power of collaborative systems pertaining to groups of robots and other complex systems. An example is the cooperative activity of robots or communication systems with changing relative topology in the battlefield. Research areas include the mathematical foundations of system theory, communication nets, the swarming phenomenon, game theory, large data set manipulation, decision-making, and data processing related to intelligent systems.

III. SPECIAL PROGRAMS

A. Multidisciplinary University Research Initiative (MURI) on Characterization and Mitigation of Service Failures in Complex Dynamic Systems

The objective of this MURI, coordinated by Professor Asok Ray of Pennsylvania State University, is to identify, understand, and mathematically formalize the failure modes in complex informational systems in order to modify and control the information to significantly increase its predictability and reliability. This project addresses the fundamental research issues of characterizing and mitigating, or circumventing, failures in complex informational and C2 (Command and Control) systems for mission critical defense applications. The Kickoff meeting of the MURI at Pennsylvania State University on June 1, 2001 with members of the research team from Penn State, Carnegie Mellon, Louisiana State and Duke Universities. The research areas of interest include, stochastic differential equations and extreme value theory, analysis of large data sets and pattern discrimination, control of distributed nonlinear dynamical networks, reliability and fault tolerant service.

B. The Critical Infrastructure Protection and High Confidence Adaptable Software Research Program of the University Research Initiative (CIP/SW URI) on Vulnerability Assessment Tools for Complex Information Networks

Led by Y. C. Ho of Harvard and Wei-bo Gong of University of Massachusetts, the central focus of this research program is on the development of vulnerability models for use in identifying weaknesses, comparing security strategies, and directing the allocation of security resources to improve security posture over time. The models will be useful in guiding the security resource allocation so as to improve the overall system security. The Kickoff meeting of the CIP/SW URI was conducted at Army Research Laboratory in Adelphi, MD, 23-24 May 2001 together with another CIP/SW URI Program cited in the next paragraph.

C. The Critical Infrastructure Protection and High Confidence Adaptable Software Research Program of the University Research Initiative (CIP/SW URI) on Modeling and Simulation Environment for Critical Infrastructure Protection

Led by Steve Robinson of the University of Wisconsin at Madison, this project intends to integrate diverse disciplines to provide multidisciplinary analysis, understanding, and remediation of problems in the protection of critical national infrastructures. The project includes basic mathematical and engineering analysis of structure and properties, analysis of human factors aspects both of the system operations and of the acts of intelligent adversaries including red teams, and computer-science approaches to problems such as automating detection of intrusions and responses to restore effectiveness after attacks. The work consists of activities in the following broad subareas: (1) Identification, detection and characterization of vulnerabilities; (2) Resilient system architectures; and (3) Integration, synthesis and impact.

D. On the Development of a Newton Interior Point Trust Region Method for Large Scale Nonlinear Programs
Christina Villalobos, University of Texas, Pan-American
Leticia Velazquez, Miguel Argaez, University of Texas, El Paso

The focus of this research is the development of an efficient algorithm for solving large scale general nonlinear programs. The proposed approach involves the use of interior point methodology, trust region globalization strategies and Krylov subspace methods. Newton's method is applied to a sequence of perturbed Karush-Kuhn-Tucker conditions and a trust region globalization technique is used to insure convergence from remote initial points. A new centrality region is developed to run through a set of interior points, keep iterates away from the boundaries and end up at an optimal solution. Inexact Newton methods are investigated as a method to simplify the solution of large scale problems and orthogonal projection Krylov subspace methods are developed to solve the highly indefinite and nonsymmetric linear systems associated with nonlinear programs. The resulting algorithms will be tested on Army problems related to meteorological modeling and data analysis and acoustic propagation.

E. Multidisciplinary University Research Initiative on Digital Communication Devices Based on Nonlinear Dynamics and Chaos
Larry Larson, University of California San Diego

Researchers at the University of California San Diego (UCSD), together with partners at the University of California Los Angeles (UCLA) and Stanford University developed a framework for radio-frequency and optical digital communication devices based on nonlinear dynamics and chaos. This team developed a chaotic optical (semiconductor laser) communication system that encodes and decodes at a rate of 2.5 Gbit/s. This bit rate is the highest ever reported in chaotic communication. This success demonstrates the feasibility of chaotic optical communication at the high bit rates of conventional optical communication. Digital communication based on chaos is of great current interest because of its spread-spectrum nature and the likelihood that it will provide superior security in wireless systems. The MURI team developed an algorithm for choosing the parameters of a chaotic encryption scheme so that security is maintained and the communication burden is not increased. This algorithm consists of guidelines for choosing the conditional Lyapunov exponent, the modulation dynamic range and the bin size so that the reconstruction error encountered by the unauthorized user, even a user using higher-order estimation techniques such as high-degree polynomials and splines, will be large but the synchronization is still fast and the power requirement is still low.

F. Multidisciplinary University Research Initiative on Data Fusion in Large Arrays of Microsensors (Sensorweb)
Alan Willsky, Massachusetts Institute of Technology

A team of researchers at the Massachusetts Institute of Technology, Princeton University and the University of Illinois at Urbana-Champaign is developing a framework for data fusion in large networks of acoustic, seismic, electric-field, magnetic and other "myopic" sensors with strong constraints on power and communication. Current designs for remote and unattended sensor arrays usually emphasize functionality of individual sensors and performance of small arrays and do not focus on information processing under military constraints. The MURI team has developed distributed, "particle"-based algorithms for localization in sensor networks, a scalable, communication- and power-sensitive, message-passing algorithm for distributed data association, sparse signal reconstruction, fast methods for computing information-theoretic quantities for data association and target discrimination, information-theoretic methods for intelligent sensor querying and a "network formation" approach that allows nodes in an ad hoc network to negotiate to form a graph to route communication traffic.

G. Department of Defense Experimental Program to Stimulate Competitive Research (DEPSCoR)

The objectives of the DEPSCoR program are to: (1) enhance the capabilities of institutions of higher education in eligible States to develop, plan and execute science and engineering research that is competitive under the peer review systems used for awarding Federal research assistance, and (2) increase the probability of long term growth in the

competitively awarded financial assistance that universities in eligible States receive from the Federal Government for science and engineering research. Under the DEPSCoR program, the Mathematical Sciences Division at ARO supports the following program:

(1) Efficient Approximations to Minimum Cost QoS Routing in Communication Systems and VLSI CAD Systems

How does one place a minimum number of receivers/transmitters so that an assortment of armed vehicles can be connected via a wireless mobile network? How should this network be updated in response to movements of some or all of the armed vehicles? Given a communication system where each link has a known cost and delay, how can one find a minimum cost routing of a given message from its source to its destinations, while satisfying a set of pre-defined delay constraints? These problems are NP-hard and as a result, optimal solutions can not be determined quickly. Guoliang Xue (Arizona State University) and Jianke Yang (University of Vermont) are developing polynomial time approximation algorithms with provably good performance for addressing these and other quality of service (QoS) problems in both communication and VLSI CAD systems.

(2) Performance and Reliability of Large-scale Disk Arrays

Performance and reliability are major concerns in the design of large disk arrays. In particular, defense applications require highly reliable storage systems with the requisite reliability being maintained without undue loss of performance. Professor Charles Colbourn (Arizona State University) and Alan Ling (University of Vermont) address these concerns by developing double erasure codes in a combinatorial setting that treats both (performance and reliability). Previous work has treated them independently and the hypothesis here is that treating them together will lead to a more economical and higher performing Input/Output (I/O) subsystem.

(3) Mathematical Study of Phase Transition Problems
Harumi Hattori, West Virginia University

The existence and the large time behavior of phase transitions are important for materials processing. In this project, an entropy rate admissibility criterion was extended to a mixed hyperbolic-elliptic system describing a solid-solid phase transition. The non-isothermal case was considered. The topics under investigation include the effect of latent heat in the dynamic phase transition, the influence of the entropy condition and the possibility of three phase boundaries. All of these topics are oriented toward defining the "design space" from which materials processors can choose techniques to create new solid materials.

H. Historically Black Colleges and Universities/Minority Institutions (HBCU/MI)

To assist HBCU/MI in building their capacity to participate in defense research activities, DoD continues to provide support to enhance programs and capabilities in science, engineering, and mathematical science disciplines critical to national security functions

of DoD and to increase the number of under represented minority graduates in these disciplines. Under the DoD Infrastructure Support Program for HBCU/MI, the Mathematical Sciences Division at ARO supports the following programs:

(1) Applied Mathematics Research Center
Fengshan Liu, Delaware State University

This research center focuses on four research tasks and one educational task. The research is on three-dimensional ground penetrating radar (GPR) imaging, non-uniform rational B-splines (NURBS) for representation of three-dimensional objects, signal processing in data mining and integration of the retransposon Tfl into chromatin. These topics are important for landmine detection, visualization, real-time provision of information and medical immunization. The educational side of this project is a summer program for minority female high school students called GEMS (Girls Explorations in Mathematics and Science) for 20 high-potential students entering the 10th and 11th grades.

(2) Vector Multiresolution Inverse Scattering and Target Detection in Multifrequency Ground Penetrating Radar Imaging
Fengshan Liu, Delaware State University

A new algorithm with a Laplacian regularizer for fixed-offset ground penetrating radar imaging was derived. In synthetic aperture radar imaging, image artifacts are common due to the motion of the radar, the inaccuracy of the motion compensation system and the non-uniform and possibly aliased sampling of the data along the radar path. To eliminate the artifacts, a new back-projection technique for ultra-wideband synthetic aperture radar imaging has been developed and is being tested by the Army Research Laboratory.

(3) Multiwavelets and Multiresolution Analysis of NURBS Curves and Surfaces
Jian-Ao Lian, Prairie View A&M University

The multiresolution structure of NURBS (nonuniform rational *B*-splines) with arbitrary (simple or stacked, uniform or nonuniform) knot sequences and of their associated wavelets, called NURBlets, has been clarified. NURBS representation of a quadrant of the unit circle has been demonstrated by using the NURBlets. Analytical formulation of spline refinement with arbitrary knots is carried out using computationally inexpensive divided differences. Multi-wavelets and their corresponding decomposition/ reconstruction filters have been constructed for two scaling function vectors of dimension 2. It has been shown that symmetry and antisymmetry of the filters can be achieved. These results are important for rapid, progressive transmission of images in Army visualization systems.

(4) Nonlinear Oscillation of Elastic Membranes
Vladimir Varlamov, University of Texas Pan American

In this project, the oscillation of a nonlinear elastic membrane under the influence of an incident acoustic wave in being investigated with the objective of developing new acoustic sensors with increased capability of finding direction to a source. An algorithm was developed for finding the vertical deflection of a nonlinear membrane and comparison with the linear case was made. The current work is oriented toward determining dependence of direction to the acoustic source on the distribution of crests and troughs of deflection. The use of nonlinearity for minimizing the spatial dimensions of the membrane detector is also under investigation.

(5) Adaptive, High-Resolution Simulation Methods for Wave Propagation in Heterogeneous Media
Thomas Hagstrom, University of New Mexico

Wave propagation problems are of fundamental importance in many areas of applied technology, particularly, but not exclusively, associated with the long-range detection and identification of various objects. They encompass a wide range of physics, including electromagnetics, fluid and solid mechanics, but share essential mathematical features. They are computationally challenging because they typically involve disparate spatial scales -- from the geometrical details of scatterers through a range of wavelengths to the propagation distances.

This effort focuses on the core numerical technologies required for the efficient and reliable simulation of waves in the time domain. These include:

  i. The development of high resolution discretizations with minimal points per wavelength in complex geometries.
  ii. Multi-physics capabilities including acoustic, elastic and electromagnetic waves in anisotropic and nonlinear media.
  iii. Automatic space-time adaptivity.
  iv. Accurate, adaptive computational domain truncations.
  v. Incorporation of the new technologies in a comprehensive research code.

(6) Synthesis and Analysis of Scattered Data
Hrushikesh N. Mhaskar, California State University - Los Angeles

In many interesting applications, one encounters the problem of approximating a function and/or determining certain local properties of a function, such as the location of singularities. Classical approximation theory typically requires knowledge of the values of the target function at judiciously chosen points. There is a growing body of applications, however, where one is not at liberty to choose these points, i.e., the data is "scattered." This researcher investigates these problems in the context of approximation and analysis of functions on a Euclidean sphere using data collected at scattered sites. A

Mathematical theory of zonal function networks for the approximation is under development as well as the construction of zonal function multi-scales for the analysis of local properties of the function. The main areas of application will be multi-source direction finding with degraded antennas and intelligent sensor fusion. The problem of direction finding can be viewed as a problem of detection of the singularities of a function given its Fourier coefficients. Then, multi-scales can be used to determine the directions and amplitudes of the incoming signals without any prior knowledge of the number of the signals or their statistical properties. The problem of data fusion is viewed from a function approximation point of view where this researcher's theory will be used to develop an intelligent process for determining whether fusion is appropriate, and if so, how to accomplish it efficiently.

IV. SCIENTIFIC ACCOMPLISHMENTS

Some New Results in Mathematical Statistics with Applications in Microarrays
Rao Chaganty, Old Dominion University

The statistical analysis of longitudinal or repeated measurements data has become a significant and growing area of research in recent years. Such data occur naturally in a range of scientific problems, including social, biological, and medical studies conducted in the Army. In recent years, the method of generalized estimating equations (GEE) has become a popular tool for analyzing such data. The seminal paper of Liang and Zeger (1986) has been cited more than 2,000 times, and the number keeps growing. No other statistical methodological paper ever received that many citations or even comes close. Also, the number of papers published in highly ranked statistical journals on the GEE method would easily exceed 300. Indeed, the GEE method has stimulated so much research interest that it earned a place in Johnson and Kotz's "Breakthroughs in Statistics, Volume III." In the last eighteen years, the National Institute of Health (NIH) has spent multimillion dollars on the development of the GEE method and GEE software, and continues to spend more research dollars.

Despite its popularity, the GEE method has some significant problems, particularly in its estimation of the correlation between the repeated measurements taken on each subject. Professor Chaganty has developed an alternative to the GEE method. His method, known as quasi-least squares (QLS), is based on the principal of generalized least squares and the theory of unbiased estimating equations. It has a strong theoretically foundation, and overcomes the problems associated with the GEE method in estimation of the correlation parameters.

Several papers have been published based on his new method, and much work remains to be done. Other researchers are slowly realizing the depth and importance of his QLS method. Research papers discussing his new method have started appearing in reputed statistical journals, e.g., Biometrika and the Journal of the American Statistical Association, which is the most cited math sciences journal in the world.

Stochastic Analysis and Control of Turbulence and Nano-Physics Subjected to Adverse Noise

S. S. Sritharan, University of Wyoming

The objective of this research is to utilize methods of advanced stochastic analysis to identify model validity ranges, assess the impact of noise and to devise robust estimation and control techniques for classical and quantum fluid dynamics subjected to space-time jump noise processes. Research is motivated by estimation and control type problems of Army relevance such as rapid sensing of biological species spreading in the air, shear layers in highly vortical flows of helicopter aerodynamics and in flame front dynamics of combustion as well as micro-fluid dynamics for soldier nano-devices. This research builds upon 15 years of DoD (ONR & DARPA) funded work by the PI in control and estimation of hydrodynamics.

The novelty of the approach is the study (i.e. control and estimation theory) of nonlinear partial differential equations of classical and quantum fluid dynamics subjected to "adverse" stochastic forces characterized with the help of infinite dimensional Levy processes, which contain (by Levy-Khintchine-Ito decomposition theorem) Wiener process as well as small and large jump type Poisson processes. In this way we consider hybrid stochastic forces that are both Gaussian and Poisson type. Main scientific barriers include the analysis of space-time discontinuous random fields as solutions to stochastic fluid dynamics in order to characterize space-time statistical solutions and to devise nonlinear filtering techniques and feedback control synthesis of relevant dynamic programming equations. Current literature on control and filtering theory of stochastic fluid dynamics deal with white noise forces, which can be characterized as generalized derivatives of Brownian sheets (Wiener fields) thus are continuous in space-time. Main challenge at hand is to extend this subject to incorporate bona-fine space-time discontinuities. Noise in Army type applications often arises, as sudden "epochs" and thus a break-through in proposed research activity will make a major impact.

Mathematical formulation and statistical analysis of stochastic Navier-Stokes equations with Levy noise is accomplished and the results will be reported in the forthcoming SIAM Annual Meeting at Oregon in July. Sensitivity of localized noise (called irreducibility of stochastic transition probability associated with the random field) was proven by proving equivalent controllability property for Navier-Stokes equation with localized control with "Navier-slip" boundary conditions which model shear layers and slip streams in highly vortical flows. Analysis of optimal stopping problem for stochastic Navier-Stokes equation to characterize impulse-in-time random forces has been completed.

- Feasibility of developing control and estimation theory of fluid dynamics subjected to space-time jump noise seems eminent.
- Infinite dimensional Levy-Khintchine-Ito decomposition of space-time random fields in to continuous and jump part is useful in the study of fluid physics subjected to adverse noise.

- Initial building blocks for the study of fluid dynamics and nano-physics subjected to adverse noise has been accomplished based on previous work on Gaussian noise case and modern results on stochastic analysis of infinite dimensional Levy (infinitely divisible and stable) processes of infinite moments.

Shape Representation, Reconstruction, and Recognition: A Comparative Study of Fourier Descriptor, Wavelets and Fractals
Calyampudi R. Rao, Pennsylvania State University

Professor C. R. Rao, the Eberly Family Chair in Statistics and director of the Center for Multivariate Analysis at Pennsylvania State University, was among the fifteen distinguished scientists who received a **National Medal of Science** from President Bush on May 9, 2002. Professor Rao was recognized for his outstanding pioneering work in multivariate analysis that has become the foundation of statistics and has had a significant impact on applications in medical diagnosis, evolutionary genetics, and signal detection theory.

Many of Professor Rao's recent research projects had been partially supported by ARO grants. In this recent research project, he successfully studied the shapes of objects, which do not have specific landmarks such as boundaries of objects. His research effort had been to extract features, which allow reconstructions of boundaries of different images that are translation, rotation and scaling invariant. The specific accomplishments in this project include: (1) development of methods for comparing different representations; (2) exploration of optimal use of features in object recognition and classifications; and (3) extension of work to build image search engines for the Internet.

The results of his research project will have important applications in improving automatic target recognition for future Army operations.

Innovative Computational Methods for Inverse Problems in Imaging
Robert Plemmons, Wake Forest University

High resolution images are essential in many important applications in defense, science, engineering, law enforcement, and medicine. The need to extract meaningful information from degraded images is especially vital for such DoD applications as integrated optical imaging systems and surveillance photography. Sources of image degradation vary among application areas but include atmospheric turbulence, turbidity in a fluid medium, defocus blur, motion blur, insufficient sampling, and electronic noise.

The objectives of this grant are to conduct rigorous mathematical and engineering research on inverse problems arising in the areas of: (1) integrated imaging systems design and implementation for image quality control, (2) image post-processing using direct and iterative de-convolution techniques and phase retrieval, and (3) accurate corrections to phase aberration problems encountered in optical and other sensor systems. The goals of this project also include providing novel and extensive research to help develop, along with an industrial partner CDM Optics Company (CDM), a reliable, easy

to use, low cost iris recognition system for personal verification, in part for computer access security at government facilities. The technical motivation is to make iris recognition easier to use by greatly expanding the iris capture volume of the imaging system. It is estimated that the methods being developed under this grant can increase the iris capture volume by greater than one hundred times compared to current iris recognition systems. For example, phase-encoding optical images in the pupil plane and then digitally restoring them can greatly improve their quality by removing certain aberrations such as defocus. However, the design of overall optical masks is a non-trivial problem and involves the numerical solution of highly non-linear and ill-posed optimization problems with multiple design parameters.

Accomplishments this year have been related to automated iris recognition which is a promising method for noninvasive verification of identity. Although it is noninvasive, the procedure requires considerable cooperation from the user. In typical acquisition systems, the subject must carefully position the head laterally to make sure that the captured iris falls within the field-of-view of the digital image acquisition system. Furthermore, the need for sufficient energy at the plane of the detector calls for a relatively fast optical system which results in a narrow depth-of-field. This latter issue requires the user to move the head back and forth until the iris is in good focus. The depth-of-field problem was addressed by studying the effectiveness of specially designed aspheres that extend the depth-of-field of the image capture system. Laboratory experiments were used to produce representative captured irises with and without cubic asphere masks modifying the imaging system. The iris images were then presented to a well-known iris recognition algorithm proposed by Daugman. In some cases unrestored imagery was presented and in other cases the moderate blur was restored by introducing the asphere. Results indicated that the use of such aspheres does indeed relax the depth-of-field requirements even without restoration of the blurred images. Furthermore, it was found that restorations that produce visually pleasing iris images often actually degrade the performance of the algorithm. Also, different restoration parameters were examined to determine their usefulness in relation to the recognition algorithm.

Handling Large, Noisy, and Under-Sampled Data in Sample Based Shape Modeling
Tamal K. Dey, Ohio State University

Many applications in science and engineering need computer modeling of physical objects for simulation, analysis, and/or design. Until recently, most applications modeled these objects synthetically. An alternative approach has gained popularity where physical objects are transported to the virtual world through scanners. Recent advances in scanning technology are making this approach more viable and attractive because these scanners can generate a set of dense points on the surface of an object extremely quickly. However, these points still need to be appropriately processed for producing a digital copy of the object and subsequently for other modeling purposes. This has opened up a new paradigm for shape modeling to which computational geometry can contribute significantly called Sample Based Shape Modeling (SBSM). SBSM potentially provides a unified approach to geometric modeling across a variety of application domains and disparate scanning methods.

Needless to say, the success of SBSM very much depends on the quality of the surface reconstruction algorithms and software. Various algorithms with different capabilities have been proposed and developed recently. However, current state of the art faces difficulty in handling large, noisy, and under-sampled data. The purpose of this grant is to address these issues.

A major accomplishment of this effort has been the development of an algorithm and resulting software named Tight Cocone that can reconstruct surfaces that are water tight. Certain CAD applications, such as creating a prototype from a model boundary, require a water-tight surface, i.e., no hole should be allowed in the surface. Recently, several algorithms have been developed that have a theoretical guarantee of computing a topologically correct and geometrically closed surface under certain conditions on sampling density. Unfortunately this sampling condition is not always met in practice due to noise, non-smoothness, or simply due to inadequate sampling. This leads to undesired holes and other artifacts in the output surface. Tight Cocone overcomes this under-sampling problem.

Tight Cocone first computes a preliminary surface using Cocone, a surface reconstruction algorithm previously developed by this group. This first step almost completes the reconstruction except in the vicinity of under-samplings. A subsequent marking and peeling completes the reconstuction by filling in all holes. This phase computes the output surface as the boundary union of Delaunay tetrahedra. This guarantees that the surface cannot have any hole though it may contain non-manifold properties where under-sampling is extreme. Furthermore, in achieving water-tightness, Tight Cocone does not introduce any extra points but rather finds triangles from the Delauney triangulation to fill up the gaps.

Digital Communication Devices Based on Nonlinear Dynamics and Chaos (MURI)
Larry Larson, University of California, San Diego

For wireless radio communication, it was shown that the best digital communication techniques based on nonlinear dynamics and chaos have bit-error-rate performance comparable to traditional non-chaotic systems, but with far greater security and low-observability. An optoelectronic-feedback laser system with encoding/decoding at a world-record 2.5 Gb/s, which matches the requirement of the OC-48 standard, was designed, built and successfully operated. There are no remaining major technical hurdles to chaotic optical communication via high-speed semiconductor lasers at the OC-192 standard of 10Gb/s. These results will lead to increased security and low-observability in Army wireless radio and optical communication systems.

Data Fusion in Large Arrays of Microsensors (Sensorweb)
Alan Willsky, Massachusetts Institute of Technology

In the many situations in sensor arrays, the data of interest can be arranged in a matrix form (sensors versus objects detectable by the sensors). Only a small fraction of the entries of the large data matrix are known. The goal is to accurately predict the

remaining entries. The MURI team has developed collaborative predictive algorithms that make use of shared properties across sensors and objects. The team developed new algorithms and a theoretical analysis of collaborative prediction based on extending the maximum margin concept from supervised learning to sparse matrix completion problems. The estimation task is formulated as a convex optimization problem via trace norm regularization, and can be solved efficiently in the dual form, a sparse semi-definite program. The generalization performance analysis, through the use of Rademacher complexity, is the first published generalization analysis of matrix completion methods.

Accurate, Data-Compressed Representation of Terrain by L_1 Splines
John Lavery, Army Research Office
Shu-Cherng Fang, North Carolina State University

The topics of this research project have been a new class of Cartesian-coordinate and curvilinear-coordinate cubic L_1 interpolating and smoothing splines. The team working on this project developed: (1) a geometric programming framework for univariate and bivariate Cartesian-coordinate cubic L_1 splines and for univariate Cartesian-coordinate cubic L_1 smoothing splines, (2) a computationally efficient active-set algorithm for computing univariate Cartesian-coordinate cubic L_1 splines, (3) theoretical results explaining some of the excellent shape-preservation properties (preservation of linearity and convexity) of univariate Cartesian-coordinate cubic L_1 splines, and (4) design of an algorithm for spherical-coordinate cubic L_1 splines. Computational experiments indicate that both of Cartesian- and spherical-coordinate cubic L_1 splines preserve the shape of multiscale data better than conventional cubic splines.

Analysis and Control of Cellular Bistable Lattices
Andrej Cherkaev, University of Utah

The focus of this project is analysis and design of bistable lattices for development of a composite armor material of increased strength. Bistable lattices are those that have a nonmonotonic force-versus-elongation relation due to the presence of "waiting elements" that affect this relation only after a certain amount of strain has taken place. Under high rates of deformation/loading, some elements of the links begin to deform plastically and thus provide a reduced effective stiffness while other elements undergo rotations with increasing deformation and begin to load, thus providing an increasing stiffness. The design optimization process is focusing on utilizing both the nonlinear material response and geometric variables of the link geometry (such as element curvature, length, and relative cross sectional area) in concert to produce the optimal global response.

Mathematical Models for Quality-of-Service-Based Routing in Networks
Erol Gelenbe, University of Central Florida

Network Quality of Service (QoS) criteria of interest in military and civilian contexts include throughput, delay, loss, jitter, poser, reliability and security. Network routing has strong influence on these metrics. However, in the past, these metrics have not been directly used as the basis for network routing policies. This project is developing a

probabilistic theory of QoS-based network routing and to determine conditions under which QoS-based routing policies exist and are unique. Incremental routing policies constructed by taking the product of routing probabilities at selected nodes have been developed. These policies are distributed and scalable. The other properties of these routing policies are currently under investigation.

On Models for Coordination Activity and Its Disruption
Joseph Lakey, New Mexico State University

This project has developed a simulation platform called *Ping II* simulation platform, which is a two-dimensional extension of a previous one-dimensional platform *Ping I*. Ping II is based on a threshold-delay model in which N agents inhabit a two-dimensional square grid with K nodes. This model was constructed using psychological and social systems principles. The current research is oriented toward equipping agents with more powerful rational and non-rational skills in order to bring the system closer to reality, especially the reality of the unexpected cultural habits that often occur in asymmetric warfare.

Networking Research: Analytical Theory of Protocols
Steven Low and John Doyle, California Institute of Technology

This project has focused on the development of a protocol theory. The three major results of the past year have been: (1) cross-layer optimization of congestion control, minimum-cost routing and resources allocation in TCP/IP networks, (2) a first-principles approach to understanding the Internet's router-level topology and (3) paradoxical behavior of TCP networks. The focus of the investigation in the third area has been the question of whether a fair allocation is always inefficient. The research characterized exactly the tradeoff between fairness and throughput in general networks. It was proved under reasonable assumptions that a fairer allocation is always more efficient. In particular, max-min fairness can achieve a higher throughput than proportional fairness.

Swarming in Two and Three Dimensions
Andrea Bertozzi, University of California at Los Angeles

This project is oriented toward developing models of swarming based on bio-sociological principles (rather than artificial principles, often those from fluid dynamics). Incompressible two-dimensional swarms lead to an integrodifferential equation for the boundary of the mill vortices. The pattern formation and stability characteristics of these swarms are currently being investigated. Compressible two-dimensional swarms lead to aggregative behavior. Application of these techniques to swarms of military interest, which will typically be low in number (tens or hundreds) is in process.

Multiresolution Representation of Terrain in the Hausdorff Metric
Ronald DeVore, University of South Carolina

This project is oriented toward compression of Digital Elevation Maps (DEMs). DEMs are usually rendered as 3-D surfaces and image processing techniques are not appropriate for processing these maps. This project is developing data compression in new metrics (such as the Hausdorff metric) that are consistent with the geometry of DEMs and are related to human use of DEMs (for line of sight, mission planning, simulation, real-time navigation, etc.). One element of the research is the development of algorithms and encoders for DEMs. Many military applications are heavily dependent upon accurate representations of enormous terrain data sets that must be provided in compressed form in order to be processed in time-critical situations. The existing compression technology for DEMs is based on least squares procedures that are known to yield poor accuracy. Project personnel are developing computational algorithms for adaptive compression with near optimal bit allocations in various non-least-squares metrics that respect geometric features of DEMs and deliver them in progressive encoded bitstreams. The DEMs are decomposed through a procedure that first identifies critical points, extracts the contours through those points in order to represent the DEM as a nonlinear superposition of maximal monotone sections. Variational procedures involving application-specific metrics are then applied to quantize and threshold the sections

PHOCI : Photonic Communications Imager
Dale Martin, Clifton Labs

The team working on this project has developed an optical system, called PHOCI, that is suitable both for image capture and for transfer of data. This system is based on a novel image/data capture chip in which high-speed optical data communication receiver technology is embedded into the image capture array of a digital video camera system. The system includes a hardware interface that allows passing both image and optical communication data through a link to a COTS host computer. A graphical user interface allows the system operator to see the camera image along with the location and recent movement vector for communication sources in the image. This system is suitable both for military applications such as optical communication in a sensor network and for civilian applications such as monitoring in a factory.

Using Evolvable Curves to Track Dynamic Boundaries
Vikram Manikonda, Intelligent Automation, Inc.

This project has demonstrated the feasibility of tracking dynamic boundaries by a swarm of robots using a level-set-based algorithm. A "market-based" optimal rate control strategy is used for networking the robots. With appropriate choices of utility and price functions, one can achieve a communication allocation scheme that is stable irrespective of feedback delay. The next phase of this work will be optimization of the algorithms and development of a prototype testbed using mobile robots. Military interests in this technology are related to tracking enemy troop and material movements.

Distributed Sensing and Processing: A Graphical Model Approach
Jose Moura, Carnegie Mellon University

This DARPA-funded project addresses decision making in distributed sensor networks under strong limitations on power, bandwidth and computing capacity. Traditionally, tradeoffs between sensor network parameters like number of sensors, degree of quantization at each local sensor and signal to noise ratio (SNR) have been investigated asymptotic assumptions on the number of sensors, an approach that often leads to not taking important details such as the structure of the fusion center into account. This project adopted a non-asymptotic approach and optimized both, the sensing and the fusion, with respect to the probability of detection error. The optimal fusion rule has a structure similar to the majority-voting rule. Convergence is SNR-dependent and, in low-SNR environments, may require a large number of sensors. Fast fusion algorithms based on message passing schemes (of the type of sum-product algorithm and belief propagation) to combine the soft decisions (probability distributions) produced by each sensor have been developed. These fusion algorithms can fuse very large networks of sensors monitoring a very large number of targets.

Wave Propagation in Photonic Bandgap Materials
Stephanos Venakides, Duke University

This project has developed computationally efficient procedures for determining the photonic bandgap properties of linear and nonlinear optical composites. The principal investigator has implemented these procedures in proof-of-principle computer codes to determine and design materials with specific bands that are or are not transmitted and for generation of second and third harmonics. The codes, which are for both 2D materials and 3D slab structures, are based on the boundary element method, which requires Professor Venakides' new analysis for determining Green's functions of complicated materials and structures. This research is important for Army needs in protection from lasers and optical communication.

Bivariate and Trivariate Macro-Elements for Surface Fitting
Larry Schumaker, Vanderbilt University

This project has developed new elements for spline tools for geometric modeling. Conventional spline elements are often not optimal with respect to (minimal) number of degrees of freedom and (maximal) approximation power. Professor Schumaker has developed optimal elements on triangulated quadrangulations that are appropriate for modeling scattered data. This work has important applications in modeling of natural and urban terrain, geological modeling, meteorology, representation of mechanical surfaces, visualization and image processing of interest to the Army.

Optimization of Structural Topology in the High-Porosity Regime
Robert Kohn, Courant Institute

This project has examined optimization of high-porosity materials and structures. In the past, it had been hypothesized that maximal stiffness could be achieved using multiscale architecture. Professor Kohn has demonstrated that, in two dimensions, maximal stiffness is achieved by a simple class of closed-cell high-porosity composites that he calls "single-scale laminates." He has shown that the task of structural optimization for minimum weight and maximal stiffness is a convex optimization problem. These results are important for design of lightweight structural and armor materials for the Army.

Signal Reconstruction and Analysis via New Techniques in Harmonic Analysis
Stephen Casey, American University

This project is developing a "coprime" sampling method and theory to estimate hop period and separate observed co-channel frequency-hopping radios. This method is based on a new approach to multi-rate sampling involving interlinked bases for which the interlinking is achieved via number-theoretic conditions. The method allows separation of signals that was not previously achievable. The method also provides a new approach to multi-rate A-D conversion that generalizes the conventional approach of having several parallel A-D converters. The coprime multi-rate approach allows the A-D converters to run at different rates without the need for signal preconditioning (for example, bandpass filtering).

High Order Numerical Methods for Convection Dominated Problems
Chi-Wang Shu, Brown University

This project involves the study of numerical methods for nonlinear hyperbolic conservation laws. The emphasis is on high order methods for resolving discontinuous or near discontinuous solutions while maintaining high order accuracy. In particular, the emphasis has been on Discontinuous Galerkin methods and Weighted Essentially Nonoscillatory finite difference methods.

During the most recent performance period, Professor Shu has developed a local post processing technique to improve the accuracy of discontinuous Galerkin methods. This technique is based on an earlier technique, originally developed by Bramble and Schatz, that was applied to continuous finite element methods for elliptic partial differential equations. Recently, Shu, Cockburn, Luskin and Suli found a way to extend this technique to discontinuous Galerkin methods and hyperbolic problems. This is a more difficult problem because the solution to elliptic problems is smooth. Hyperbolic problems often have discontinuous solutions. The latest work involves the development of a one sided post processing technique for improving accuracy near boundaries, shocks and interfaces between domains with different meshes. Extensive numerical testing has shown that the technique is very effective for improving the convergence of derivatives, for solving multi-domain problems with different mesh sizes in the different domains; variable coefficient linear problems including those with discontinuous coefficients; and

linearized Euler equations applied to aeroacoustic problems. The post processing technique produces an improvement in order of accuracy from order k+1 to 2k+1 for the discontinuous Galerkin method with piecewise polynomials of degree k. This improvement shows up throughout the entire domain.

Quasi-Monte Carlo Methods for Markov Chain Problems
Michael Mascagni, Florida State University

In its simplest form, the idea behind quasi-Monte Carlo methods is to replace the pseudo-random numbers used in conventional Monte Carlo methods with uniformly distributed numbers from a deterministic sequence. If the number of samples required is known and if the dimensionality of the problem is small, points on a grid would be the most uniform. However, if the dimensionality is large and the number of samples is not known a priori, quasi-random sequences developed by number theorists seem to work best.

In earlier work funded by ARO, Caflisch showed that quasi-Monte Carlo Quadrature methods converged at a rate of $O(n^{-1})$ which is considerably faster than the $O(n^{-1/2})$ of conventional Monte Carlo methods. In this work, Mascagni extended these results to other numerical problems; in particular, he examined problems from linear algebra.

From a theoretical point of view, he was able to reformulate linear algebra problems as the evaluation of integrals or as the solution of integral equations with special kernels and domains. Thus, these problems can be analyzed using the quadrature results developed earlier. As a result when quasi- Monte Carlo is applied to the solution of large, sparse matrices, it outperforms conventional Monte Carlo methods as expected. Better yet, the quasi-Monte Carlo method shows excellent parallel efficiency.

Motivated by numerous problems in statistical physics and quantum mechanics which require more than just the dominant eigenpair, Mascagni studied the use of deflation and quasi-Monte Carlo power iterations to compute both the first and second largest eigenpair. Theory, confirmed by numerical experimentation, showed that this approach consistently outperformed methods based on conventional Monte Carlo methods.

V. TECHNOLOGY TRANSFER

The main thrust of the extramural program is the development of new scientific ideas. In order for these ideas to have an impact on the Army technology base, they must be imparted to the scientists, engineers, and analysts in various Army agencies. Presently, this transfer of new knowledge is being accomplished by a variety of both direct and indirect means including bringing ARO investigators into direct contact with Army scientists and engineers. This approach to technology transfer has proven to be very productive. Examples of various ways in which these interactions are encouraged follow.

A. Direct Interactions

Numerous collaborative efforts between researchers and Centers of Excellence on the one hand and Army personnel on the other are now taking place. Collaboration with personnel in Army laboratories and commands is occurring in nearly all of the projects supported by the Mathematical and Computer Sciences Division. Below, we present a few examples of such interactions.

Linear and Nonlinear Solvers for Subsurface Flow
C. T. Kelley, North Carolina State University

Modeling and simulation is needed to design remediation systems for environmental cleanup of toxic waste sites at Army and other DoD facilities. Scientists at the U.S. Army Corps of Engineers Research & Development Center (ERDC) in Vicksburg, MS have developed ADH, a computer program to simulate surface and groundwater flow. The models used in this program have non-smooth nonlinearities. This has a negative impact on the convergence of the nonlinear equation solver. The problems, which need to be solved, are very large, so the computing needs to be done on distributed memory parallel computers. Professor C. T. Kelley from North Carolina State University and his students have been addressing these problems. Their analysis of the non smooth nonlinearities which occur in these problems, takes into account the effect of finite difference approximations to generalized derivatives, pseudo-transient continuation algorithms for finding steady state solutions and methods for solving problems with differential algebraic dynamics. This analysis has led to the development of a new temporal integration algorithm and a pseudo transient continuation algorithm, both of which have been implemented in ADH.

Muzzle Brake Analysis Software
Joseph Flaherty and Mark Shephard, Rensselaer Polytechnic Institute

The muzzle brake is a device which is attached to the end of a large caliber gun to deflect the propellant gases and reduce recoil. A side effect of the use of a muzzle brake is an overpressure which can cause permanent hearing loss to the soldiers who fire the guns. Therefore it is important to understand the details of the flow through muzzle brakes in order to come up with new designs which maximize recoil attenuation while keeping overpressure within safe bounds. With ARO funding, Professors Joseph Flaherty and Mark Shephard from Rensselaer Polytechnic Institute have developed new software for predicting overpressure and recoil in perforated muzzle brakes. This software uses a Discontinuous Galerkin method, unstructured grids and adaptive grid refinement. The software has been parallelized and can solve three dimensional problems on different computer architectures ranging from laptops to supercomputers. This software has been transitioned to the Benet Weapons Lab. Interfaces to Fluent's Gambit and the Ensight 7 systems were developed to comply with Benet's pre and post processing environments. This software provides the laboratory with a state of the art tool for understanding the effects of blast over pressure and for developing systems to reduce it.

High Order Methods for Helicopter Aerodynamics
Chi-Wang Shu, Brown University

If the wake from the main rotor of a helicopter interacts with the tail rotor or the fuselage, it could affect the stability and performance of the aircraft. These wakes cannot be tracked using low order numerical methods because such methods have too much dissipation. To overcome these problems, Professor Chi-Wang Shu from Brown University has developed an efficient multi-domain high order WENO (Weighted Essentially Non-Oscillatory) finite difference method for solving these types of problems. This method uses simple grids which are patched together. The primary accomplishment is the design of an interpolation scheme which is stable, accurate and which permits shocks to pass between domains without oscillations and at the correct speed. This allows for high order accuracy, low computational cost and relatively complex geometry. The method is currently being incorporated into the NASA Overflow computer code for use by AMCOM –AVRDEC at the NASA Ames Research Center.

Handling Massive Models: Representation, Real-Time Display and Interaction
Dinesh Manocha and Ming Lin, University of North Carolina – Chapel Hill

This project addresses some fundamental research issues in handling and visualizing massive models, composed of millions of primitives. These include efficient representations, interactive display and real-time interaction. These models arise in many DoD and civilian applications, including computer-aided design, simulation-based design, lethality and vulnerability analysis, medical simulation, simulation-based training, and scientific visualization. The goal is to develop efficient algorithms and systems, and demonstrate their performance on massive environments composed of millions of primitives. The set of research problems include:

1. Hierarchical and multi-resolution representations of models for fast display,
2. Interactive display of large polygonal, sculptured, sampled or solid models on current graphics systems,
3. Interactive proximity queries and collision response between rigid and deformable models in a large, complex environment,
4. Real-time interaction with the virtual world.

A number of techniques from algebraic geometry, approximation theory, computational geometry, numerical analysis, computer-aided geometric design and computer graphics are employed to investigate the underlying mathematical concepts and to develop more efficient and robust geometric algorithms. This includes developing algorithms and techniques for using GPUs (graphical processing units) as co-processors for general-purpose computations. This has led to a major collaboration with PEO-STRI and RDECOM to use the computational power of GPUs to speed up OneSAF (Semi-Automated Forces) and CGF (Computer Generated Forces) computations. In particular, the PIs are developing faster algorithms for line-of-sight computation, collision detection,

and route planning using GPUs. The resulting algorithms will be integrated with OOS (One-SAF Objective System)

Data Fusion in Large Arrays of Microsensors (Sensorweb)
Alan Willsky, Massachusetts Institute of Technology

The Data Fusion MURI team has developed a sparse signal reconstruction algorithm for source localization by sensor arrays. In particular, the team demonstrated that under certain often occurring conditions, the intractable combinatorial optimization problem of sparse signal reconstruction can be solved exactly by a computationally feasible convex optimization algorithm. The team conducted experiments demonstrating the source localization algorithm on acoustic data from field experiments provided by the Army Research Laboratory Computer and Information Sciences Directorate.

Accurate, Data-Compressed Representation of Terrain by L_1 Splines
John Lavery, Army Research Office
Shu-Cherng Fang, North Carolina State University

In joint work by Danny Champion of the TRADOC Analysis Center at White Sands Missile Range and John Lavery, lines of sight in natural terrain were calculated by the L_1 splines developed in this project and by various conventional methods (conventional splines, TINs, DYNTACS, Janus (old and new), ModSAF and Bresenham). The results indicate that cubic L_1 splines provide lines of sight that are as accurate as those of the best previously available procedure (DYNTACS). These previously available methods had an advantage of being implemented in adaptive frameworks while the L_1 splines were available only in a non-adaptive, uniform-grid framework. A joint presentation on this topic was given by Danny Champion and John Lavery at the 23rd Army Science Conference. This presentation was one of the factors that led to the establishment at the Topographic Engineering Center (TEC) of the Line of Sight Technical Working Group in June 2003 of which Danny Champion and John Lavery are members.

B. Interactions with the Department of Defense

The major research objectives of Dr. Harry Hurd, Harry L. Hurd Assoc., Inc. and University of North Carolina-Chapel Hill, include: (1) research on non-stationary processes and signals, but concentrating on cyclostationary (also called periodically correlated) processes and on signals with harmonic structure that have a strong connection to battlefield acoustics because trucks and tanks emit signals with exploitable harmonic structure; and (2) research on target positioning and tracking based on battlefield acoustic data. Dr. Hurd's work on cyclostationary processes is general and often structural, but covers topics such as time series methods, modeling and prediction. The general concept underlying his methods for harmonic is that coherence exists between the harmonics when they are received, and this coherence should be exploited for various purposes, including the estimation of tracking parameters and the suppression of strong signals. His work on target positioning and tracking is based on least squares batch tracking methods and on particle filtering methods. His past and current efforts

have resulted in publications and submissions of several papers (coauthored with Army scientists) and direct presentation to the ARL Acoustics branch and to the ARMY Center of Excellence in Acoustics, TACOM/ARDEC, AMSTA-ARFSF-R, and at the Symposia on Battlefield Acoustics and Seismic Sensing.

Biometrics such as iris recognition are critical to safeguarding information that is vital to national security. The US Army has a direct interest in furthering research in biometrics and is working closely with other interested government agencies. Army researchers have also been intimately involved in a revolutionary method for designing digital imaging systems that was developed at the University of Colorado. A significant application is extended depth-of-field systems that allow near and far objects to be viewed in sharp focus without a loss in light gathering ability. Army researchers and university collaborators are applying this imaging technique to biometric problems. In particular, researchers from Wake Forest University (WFU) who are experts in computational image restoration have worked closely with researchers from industry to study the effectiveness of extended depth-of-field for iris recognition. A successful outcome would enable iris codes to be measured without the need for the subject to maintain a critical distance from the camera. This interaction has led to the development and delivery of: (1) an extended-focus camera system to the National Security Agency, and (2) an iris imaging simulator system and a Pupil Phase Engineering simulator system for the Central Intelligence Agency.

Professor James Glimm and his group are collaborating with Dr. Charles Bowden and his group at Redstone Arsenal to develop photonic devices. Professor Glimm has developed a 3D parallel FDTD (Finite Difference Time Domain) simulation code with perfectly absorbing boundaries to allow the study of finite devices. This code is being used to simulate application specific device geometries and help resolve design issues. Professor Glimm's group works closely with Dr. Bowden's experimental group to model devices and optimize parameter values.

Professor Jan Hesthaven from Brown University has developed a version of the discontinuous Galerkin method for solving the time domain Maxwell's equations. This method permits high order accurate solutions to be computed in complex geometries. The method is currently being tested by researchers at the Army High Performance Computing Research Center as a tool for determining the radar cross section of ground vehicles from different angles and in different environments.

Coordination with the Army Model and Simulation Office, (AMSO), Mr. W. H. Dell Lunceford, Jr., Director, took place in August 2003, when Mr. Lunceford invited Dr. Jim Chang, Director of the Army Research Office, to visit AMSO for program coordination matters. This meeting was attended by Dr. Chang, Dr. Robert Launer of USARO, and six members of AMSO. This was followed by a workshop in Modeling and Simulation which was held in November at the ARO. The workshop featured talks by ARO Principal Investigators and other speakers from the ARO programs in the mathematical sciences as well as scientists from the Army laboratories. The workshop was well attended.

C. Other Interactions

Tamal Dey, Professor of Computer Science at Ohio State University, has been designing and developing software based on computational geometry techniques to more accurately model and reconstruct the shape of a physical object based on digitized data obtained from some type of scanning of that object. A significant result has been an algorithm, called "tight cocone," to produce watertight surfaces out of noisy under-sampled data. The Tight Cocone software has been released for public use from the web-page http://www.cis.ohio-state.edu/~tamaldey/cocone.html. This software has been registered as an innovative technology in the Ohio State University. Currently negotiations are underway for possible licensing of this software with a company called GeometryFactory. In the meantime, the medial axis software which is a part of Tight Cocone package has been licensed by a company called C-solutions.

The mesh free particle method developed by Professor Ted Belytschko at Northwestern University has been transferred to Livermore Software for use in the LS Dyna large deformation computer code. This code is heavily used at DoD laboratories for weapon design. The new method should increase the robustness of the code for large deformation and penetration problems.

The front tracking technology developed by Professor James Glimm at SUNY at Stony Brook has been adopted by many of the National Laboratories. In particular, the FronTier code is being used at Los Alamos for both fluid mechanics and solid deformation modeling; it has been merged with the Overature code at Livermore; it is being merged with the SAGE code at Los Alamos to provide both front tracking and adaptivity; and it is being used at Argonne for the simulation of jet breakup studies.

The Data Fusion MURI team is collaborating with a student who received his Ph.D. under the Data Fusion MURI and is currently at Parc Inc. in Palo Alto, CA. Ideas contained in his thesis on hierarchical estimation and distributed algorithms for inference are now being implemented in the test bed for multiple target tracking being developed at Parc. The Data fusion MURI team also collaborates with Professor Randall Moses of Ohio State University in sensor network self-localization, an area in which Professor Moses is working under support from the Army Research Laboratory Sensors Collaborative Technology Alliance.

D. Workshops

Workshops organized and sponsored by ARO and its various center activities have served not only as an effective method to impart new scientific information, but also to develop new ideas on how to attack Army problems and to interest civilian scientists in these problems. Workshops are mini-symposia organized around a well-defined mathematical topic of special interest to one or more Army research and development laboratories or activities.

IMA Workshop on Agent-Based Modeling and Simulation

In November 2003, the ARO Modeling of Complex Systems Program co-sponsored the Workshop on Agent-Based Modeling and Simulation at the Institute for Mathematics and Its Applications (IMA) of the University of Minnesota. Agent-based modeling and simulation is an approach to simulating the behavior of a complex system in which agents interact with each other and with their environment using simple local rules. The motivation for this approach is the fact that the systems under consideration are so complex that traditional approaches based on differential and integral equations are not computationally feasible. The workshop brought together leading researchers in these and other areas in which agent-based modeling is under investigation. The workshop identified fundamental scientific questions whose answers could form the basis of a sound mathematical and computational theory for agent-based modeling and simulation, highlighted recent successes and outlined future research directions in this area. Recent successes have been in sensor webs, traffic flow in metropolitan areas, the spread of infectious diseases, the behavior of economic systems and critical infrastructure.

Workshop on General Purpose Computing on Graphics Processors

For years the performance and functionality of graphics processors (GPUs) has been increasing at a faster pace than Moore's Law. Recently, the major graphics chip manufacturers have added support for floating-point computation and have released compilers for high-level languages.

These GPUs are not like the array processors of the past. First, the prices of these commodity parts are more than an order of magnitude lower—the price of the highest performance graphics cards is only about $350. Furthermore, these chips are in practically every personal computer (PC), game console and workstation sold today.

Heretofore, the primary application of GPUs has been fast rendering of anti-aliased, textured and shaded geometric primitives (e.g. polygons). Their main market has been mostly computer games and the entertainment business.

The performance and functionality of today's GPUs make them attractive as co-processors for general-purpose computations. Over the last few years, many new algorithms and applications that exploit the inherent parallelism and vector processing capabilities of GPUs have been proposed. These include:

- Scientific computation including FFTs, linear algebra solvers, differential equation solvers, multi-grid solvers and applications to fluid dynamics, visual simulation, ice crystal growth, etc.
- Geometric computations including Voronoi diagrams, distance computation, motion planning, collision detection, object reconstruction, visibility, etc.
- Advanced rendering including ray-tracing, radiosity, photon mapping, sub-surface scattering, shadows, etc.

- Database operations including aggregates, predicates, Boolean combinations, selection queries, etc. on large databases.

Given the increasing power and usage of commodity GPUs, this workshop was organized to explore general purpose computing using GPUs. Some of the issues included:

- Do GPUs have the potential of being a useful co-processor for a wide variety of applications? What are their algorithmic and architectural niches and can these be broadened?
- What are the major issues in terms of programmability, language and compiler support and software environments for GPUs?
- What are some of the future technology trends that can lead to more widespread use of GPUs?

The workshop brought together leading researchers and practitioners from academia, government, and industry working in computer graphics, scientific computation, high performance computing, computer architecture and related areas. In particular, both PEO STRI and RDECOM had a strong presence having recently become interested in utilizing GPU-based technologies for speeding up Computer Generated Forces and OneSAF computations. The program consisted of invited talks, panels, and poster presentations.

Conference on Adaptive Methods for Partial Differential Equations and Large Scale Computation

Many physical problems of interest to the Army are modeled by partial differential equations with solutions that exhibit localized nonuniformities that form, evolve and decay during integration. Examples include boundary layers and shocks in fluids and reaction fronts in combustion. Many problems or practical interest are just too large for the traditional approach of using computing meshes that are fine enough to resolve all phenomena. As a result, adaptive methods are necessary.

A conference, partly funded by ARO, was held at Rensselaer Polytechnic Institute on 11 and 12 October 2003, to bring together researchers in adaptive methods, data structures, error estimation, mesh generation, discretization methods and multiscale applications to discuss new advances and challenges. Although such methods are used in many industrial applications, much remains to be done to obtain higher resolution and better efficiency.

VI. DIVISION STAFF

Dr. Chris Arney, Associate Director
Cooperative Systems

Dr. Michael Coyle
Discrete Mathematics and Computer Science

Dr. Stephen Davis
Computational Mathematics

Dr. M. H. "Harry" Chang
Probability and Statistics

Dr. John Lavery
Modeling of Complex Systems

Dr. Robert Launer
Modeling, Simulation, and Related Mathematics

Peggy Gravitte
Administrative Support Assistant

I. PROGRAM OBJECTIVES

As envisioned by the Army's emphasis on the Future Combat System, the modern field Army must be quickly deployable to far-flung global locations with aggressive, sustainable, and lethal weaponry for obtaining clearly stated objectives with minimal losses. These requirements demand an Army equipped with lightweight but lethal and, maneuverable, and survivable ground/air vehicles that minimize logistics demands. Such vehicles and their armament systems must be highly reliable, sustainable in the battlefield environment, designed for low maintenance, highly stable both as transports and weapon platforms, protective of human occupants in battlefield environments, and must reflect minimized lift cycle cost. Weapons need to be lethal, controllable and accurate providing single shot-to-kill capability. Additionally, fortifications need to be quickly emplaced and guarantee protection against threat of both ballistic and blast nature. The provision of such a capable future Army force demands an active and healthy basic research program in the mechanical sciences, since this discipline is fundamental to the sustainment and advancement of the U.S. Army battlefield capabilities in mobility, firepower, weapon reliability, survivability, lethality, and service support.

Fundamental investigations in the mechanical sciences research program are focused in the areas of solid mechanics, structures and dynamics, propulsion and energetics, and fluid dynamics. Very special research thrusts have been continued in the Army relevant areas of rotorcraft technology, projectile/missile aerodynamics, gun propulsion, diesel propulsion, energetic material hazards, mechanics of solids, impact and penetration, smart structures, and structural dynamics.

Research contained within the Propulsion and Energetics Program is organized into elements that address engine combustion, gun and missile propulsion, and energetic materials (propellants and explosives) hazards initiation. The Fluid Dynamics Program encompasses the aerodynamics of rotorcraft, projectiles and missiles, and parachutes. The Solid Mechanics Program is concerned with the fields of response and failure mechanisms of solids under complex and severe loadings. The Structures and Dynamics Program is focused on structural dynamics and vibrations, rotorcraft aeroelasticity, composite material structural applications, structural health monitoring, and smart structures, hovering micro aerial vehicles with invertebrate vision inspired guidance systems. Under Defense Advanced Research Projects Agency (DARPA) support, research is focused on the use of micro-active flow control for application to turbine engines, tilt-rotor and conventional helicopters, and guided projectiles. DARPA is also supporting investigations of a swashplateless helicopter rotor with ferromagnetic shape memory material actuators, fuel powered and thermoelectric shape memory alloy actuators, control algorithms for actuators for helicopter rotor blades with a trailing edge flap, high strain relaxor ferroelectric materials and actuators for adaptive structures, an exoskeleton lower extremity enhancer for strength and endurance enhancement of dismounted soldiers, smart electromagnetic antenna structures, fuel cell powered high energy density artificial muscle for application in exoskeleton devices, and determining the feasibility of an underwater power generation unit and distribution system for

controlled, wearable exoskeleton devices. Under continued Missile Defense Agency (MDA) support, the research programs investigate (1) the underlying physics of missile signatures and aerothermophysics of the theater missile defense environment and (2) high precision, high frequency, fault tolerant manipulation of multiple payloads aboard a hexapod based pointing system capable of optically locking onto the position of a target over a wide field of view moving multi-axis platform controlled by active struts..

Consequently, this research program addresses a broad set of research problems in varied scientific areas. The totality of this research effort greatly contributes to the future technology base from which significant improvements in U.S. Army aviation, ground vehicles/equipment, guns, armor, and other weapon systems can be made.

II. RESEARCH PROGRAM

A. General Information

PROPULSION AND ENERGETICS PROGRAM

Motivation - Propulsion and energetics research supports the Army's need for higher performance propulsion systems. These systems must also provide reduced logistics burden (lower fuel/propellant usage) and longer life than today's systems. Fundamental to this area are the extraction of stored, chemical energy and the conversion of that energy into useful work, for vehicle and projectile propulsion. In view of the high temperature and pressure environments encountered in these combustion systems, it is important to advance current understanding of fundamental processes as well as to advance the ability to make accurate, detailed measurements for the understanding of the dominant physical processes and the validation of predictive models. Thus, research in this area is characterized by a focus on high pressure, high temperature combustion processes and on the peculiarities of combustion behavior in systems of Army interest.

Engine Combustion - Current ground and air vehicle propulsion relies on reciprocating (Diesel) and gas turbine engines, either as primary propulsion or as part of a hybrid drive system. These engines must be capable of delivering high power with high fuel efficiency. These thrusts, power density and efficiency, are the heart of the Army's initiative for the Future Combat System. The development of reliable, predictive models for vehicle engines will require advances in understanding fundamental processes, such as turbulent flame structure, heat transfer, and chemical kinetics, as well as understanding and control of the complex chain of fuel injection-atomization-ignition-combustion processes. An additional complication is presented by the high pressure/temperature environment, encountered in Diesel engines, which influences liquid behavior and combustion processes at near-critical and super-critical conditions. It should be noted that over 95% of Army vehicles are diesel-powered and that the Army desires the capability to use a single, logistics fuel (JP-8) in all engines, both diesel and turbine.

Gun and Missile Propulsion - Gun and missile propulsion relies on the rapid, controlled release of energy from high energy density propellants, which exhibit unique combustion characteristics. Modern composite, solid propellants are characterized by a complex, multi dimensional flame structure, with solid, liquid, liquid-gas, and gas phase reaction zones. The small scales of the combustion zones, typically on the order of microns, and the high pressures, up to 600 MPa, present formidable challenges for combustion diagnostics. There are systems whose future development requires new directions in combustion research. Among these is the electrothermal-chemical (ETC) gun, in which the ignition, and potentially combustion control, of solid propellant is achieved by high temperature plasmas. Concepts for advanced, variable thrust missile propulsion also pose difficult challenges, e.g. the interaction/combustion of hypergolic propellants, the development of novel combustion chambers (c.f. vortex combustors), the dynamics of pintle nozzles, etc. An underlying concern with all high energy density systems is the hazard and system vulnerability posed by the propellant. Thus, research is also needed to determine the response of these materials to inadvertent ignition stimuli and factors controlling undesired combustion behavior, such as pressure oscillations. A key goal is the coupled analysis of propellant composition, material characterization, combustion dynamics, and sensitivity.

Missile Signatures and Aerothermochemistry - The development of the capability to passively track and target missiles during flight requires the accurate prediction of vehicle environments and signatures to define the operational sensor parameters. This applies to both standoff and missile-borne sensors. Current capability to reliably predict such environments is limited by the flowfield simplifications necessary to reduce the computational complexity to within the capability of available computers, especially for hypersonic, turbulent flows. Accordingly, studies have been initiated to determine three-dimensional flowfield properties about high-speed vehicles at low and intermediate altitudes.

Investment - For FY04, a total of $3.481 million was spent to support programs in the Propulsion and Energetics area. This included $0.911 million in the Office of the Secretary of Defense (OSD) funds to support the Defense University Research Initiative in Nano-Technology (DURINT) Program in "Nano-Systems Energetics", and $200 thousand to support a new PECASE award in the nanoenergetics area, along with $209 thousand in MDA funds to support the "Missile Signatures and Aerothermochemistry" Program. These programs are discussed in Section III – Special Programs. Additionally, $102 thousand in OSD funds was used to support an instrumentation grant under the Defense University Research Instrumentation Program (DURIP). Approximately $1.92 million of Army funds were expended during FY04 on the Propulsion and Energetics Program. Of that amount, $1.821 million was Army basic research funds. A new, Multi-disciplinary University Research Initiative program, "Nano-Engineered Energetic Materials," was initiated in late FY2004. Of the total funding, approximately 27 percent went into the engine combustion area in support of 15 projects. The gun and propulsion/energetic materials hazards area received 73 percent in support of twenty one projects. This represents a major shift in emphasis compared with previous years, in

which the engine area was dominant.

Interfaces - This research effort has been closely coordinated with the appropriate Army Research Laboratory (ARL) divisions and Army Materiel Command's Research, Development and Engineering Centers (RDEC's), and in some cases, represents efforts supplemental to current in-house projects or jointly funded efforts. In engine combustion, the participating laboratories/centers are TACOM-TARDEC, AMCOM, and ARL Vehicle Technology Directorate; in gun propulsion/energetic materials hazards, ARL Weapons and Materials Research Directorate (ARL/WMRD), TACOM-Armament Research, Development and Engineering Center (ARDEC) and the AMCOM-AMRDEC. Interactions with Army scientists and engineers frequently occur during project reviews and joint support and participation in workshops, conferences, and symposiums. Additionally, close coordination is maintained with the Air Force, Navy, U.S. Department of Energy (DoE), and National Aeronautics and Space Administration (NASA) research programs with frequent discussions and several co-funded projects.

FLUID DYNAMICS PROGRAM

Motivation - The performance of Army weapon systems that involve airborne vehicles or convecting liquids is greatly affected by the fluid motion and the resultant forces imparted to the vehicle. The study of fluid dynamics is, thus, of vital interest for the design, development, and performance enhancement of many Army systems. One weapon system important to the Army is rotorcraft vehicles, whose performance depends largely on a mature and sound understanding of the fluid dynamics of such vehicles in flight. This field of aerodynamics makes possible the tactical flight operations envisioned for the highly mobile Army of the twenty-first century. The goal of more accurate, stable, maneuverable, and longer-range munitions dictates the need for aerodynamics research for both gun-launched projectiles and tactical missiles.

Research within the area of fluid dynamics over the last decade has resulted in the conception, development, and validation of a wide array of powerful new tools. In the experimental arena, the development of nonintrusive flow diagnostic methods, such as particle imaging velocimetry (PIV), holographic interferometry, and luminescent paints, is revolutionizing the study of fluid mechanics. Computationally, developments such as unstructured and Chimera grids, direct and large eddy simulation (LES), and high-speed parallel computers, have provided the capability to analyze complex fluid dynamics problems which previously were not amenable to analysis. Advances in smart materials, microelectromechanical systems (MEMS), fuzzy logic, and neural networks offer the possibility of fluid mechanics control for a wide variety of Army systems. Over the last several years the rapid growth in flow control research has demonstrated the potential for aerodynamic morphing of fluid structures by using steady and unsteady fluid excitation for separation control, flow vectoring, and increased aerodynamic loading. The application of these new tools to important Army fluid dynamics problems enables significant performance and life cycle cost improvement for many Army systems. Research within the Fluid Dynamics Program is focused on the use of these tools for

fundamental understanding of the complex fluid dynamics processes underlying these systems and involves analytical, computational, and experimental approaches.

Rotorcraft Aerodynamics - Increased performance demands on modern Army rotorcraft require the accurate prediction and control of the forces and moments generated on the vehicle in hover, forward flight, and maneuver. Accomplishing this broad objective requires, for example, research into the mechanisms underlying unsteady separation of boundary-layer fluid on the suction side of rotorcraft blades, wakes, unsteady rotor aerodynamic loads, interference aerodynamics, and computational fluid mechanics. Typical examples of ongoing research within this field are the experimental and numerical determination of the flowfield over airfoils undergoing two- and three-dimensional unsteady separation with subsequent dynamic stall, the development of micro active flow control techniques for rotor download alleviation and dynamic stall control, and the development of advanced rotor free-wake methods to improve predictive capability for helicopter performance, vibration, and noise.

Missile and Projectile Aerodynamics - To ensure the accuracy and range of unguided gun-launched projectiles and the maneuverability and lethality of guided munitions and rockets, a thorough knowledge of the forces and moments acting during both launch and free flight is required. These objectives dictate research on shock boundary-layer interactions, compressible turbulence modeling, aft body-plume interactions, vortex shedding at high angle of attack, transonic body flows, and aerodynamic interference effects between various missile components. The general research areas of turbulent flows on spinning bodies, multi-shocked flowfield structure, base drag analysis and reduction, and control jet-flowfield interactions are also relevant to this research program. Examples of current studies in this subfield are the experimental study of aft body-plume-induced separation, the use of direct numerical simulation, LES, laser-Doppler velocimetry (LDV), and PIV techniques to investigate axisymmetric supersonic power-on/power-off base flows, and the experimental investigation into the underlying physics of unsteady shock-wave/turbulent boundary-layer interactions.

Investment - During FY04 a total of about $7.5 million from all sources was committed to the support of research in the fluid dynamics area. Approximately $2.3 million of this investment came from the Army, with single-investigator projects in the areas of projectile/missile aerodynamics, helicopter aerodynamics, and dynamic parachute opening. DARPA funds totaling approximately $4.6 million were invested in micro active flow control and helicopter quieting projects.

Interfaces - This research program is closely coordinated with and supplemental to the research and development programs of AMCOM and ARL. Interactions with Army engineers and scientists occur through frequent visits to Army laboratories, Army laboratory evaluation of proposals, jointly sponsored research contracts and workshops, and at professional society meetings and ad hoc meetings in specific technical fields. In addition, a close liaison effort is maintained with DARPA and NASA. Periodic interchanges of both written and oral briefings on research program content occur with

Air Force and Navy counterparts.

SOLID MECHANICS PROGRAM

Motivation - The modern Army must be quickly deployable, weaponry must be accurate and lethal, and its equipment must be sustainable under a wide variety of adverse conditions, while also providing maximum protection. Under the Objective Force platform, future Army systems, such as the Future Combat System of Systems (FCSS) will require three-dimensional modeling of complex fracture and failure processes of light weight and high strength heterogeneous structures subjected to severe loading conditions and environments, such as shock, impact and penetration, and corrosion. Choices among a complex array of materials and manufacturing processes need to be made for optimum tactical and logistical superiority. Interrelated analytical, computational, and experimental approaches must be developed and used as predictive and design methodologies for new and significantly improved heterogeneous systems. These tools must provide a better understanding of complex phenomena at all physical and temporal scales: nano, micro, and macro. Furthermore, the interrelations and interactions between these scales must be studied to ascertain the overall physical behavior of the system and relate it to the microstructure so that new systems can be designed and developed. The major areas of interest for the U.S. Army Research Office (ARO) Solid Mechanics Program are analytical, computational, and experimental approaches pertaining to micromechanics, finite deformation, material instabilities, dynamic fracture, stress wave propagation, and damage mechanisms applied to the design and manufacturing of new and significantly improved heterogeneous structural systems. Relevant applications include armor and anti-armor systems, weapon platforms, and ammunition for Army materiel and personnel.

Mechanics of Heterogeneous Solids - Overall performance and durability of Army systems and platforms involve nonlinear complex deformation and failure modes that are encountered in the fabrication and operation of many armaments and missile components. Complex stress and strain states, and interactive failure mechanisms occur in the formation and flight of explosively formed penetrators (EFP) and shaped charge jets, as well as in penetrator and target interaction zones for armor and anti-armor systems. Understanding, analysis, and prediction of these processes can be facilitated by the development of validated and verified constitutive models that are coupled to failure criteria. These criteria can be used to both prevent overall failure and for the development of new damage tolerant resilient structures. Rate-dependent finite deformation inelastic behavior, texture evolution, criteria for the initiation of localized zones, and the nucleation, growth, and coalescence of voids and cracks are challenging scientific issues. Heterogeneous structures, which can comprise combinations of ductile and brittle materials, are candidates for a variety of Army materiel, because response and performance can be potentially tailored for desired applications. However, a lack of scientifically based frameworks for how to control heterogeneities and damage at different physical scales makes the development of accurate design techniques, scaling laws, and service-life predictions difficult, if not impossible. Currently, selected research

studies in support of these areas contain both experimental and analytical investigations. They are related to the initiation and evolution of damage in structures; micro-mechanical and continuum analyses of large deformations at high strain rates; failure modes in composites; nonlinear behavior of functionally gradient materials; micromechanics of active materials; and predictions of texture evolution and failure modes in crystalline materials.

Impact, Penetration, and Shock - A wide variety of Army materiel, such as helicopter blades, tactical missile structures, ground vehicle armor, and penetrators, are often subjected to impact loading conditions that span the spectrum of impact velocities and impulses. Vulnerability assessments and design of space- and weight-saving protection systems depend on understanding the mechanics of the phenomena. Ever-increasing demands for weight and volume efficient protective structures for armored vehicles need to be addressed by making use of inherent and external mechanisms. Novel materials, mechanisms, and systems are needed for better armor and anti-armor systems. Armor systems function by exploiting material failure in a controlled manner. Inherent in this process is a linking of physical scales to energy dissipating and absorbing mechanisms and phenomena. Topics in this area include stress wave propagation in solids, damage evolution in brittle and ductile materials, impact damage and penetration processes, which can inhibit and dissipate the penetration process. Selected current projects in the impact and penetration research are focused on shear resistance and shear localizations under high-pressure at very high rates for high-strength material combinations; three dimensional computational analyses of the penetration process for armor and anti-armor systems; failure criteria and failure mode transition in ductile materials; mechanics of long rod penetration into ceramics under confinement; stress wave management through the control of attenuation and dissipation in heterogeneous structures; modeling of cohesive failure in viscoelastic composites.

Investments - Army 6.1 funds in the amount of $ 4.2 million were invested in FY04 on research in solid mechanics to support projects in the areas of mechanics of heterogeneous solids, and impact, penetration, and shock. Added in 2004 was a MURI on Hybrid Biomechanical Systems which is investigating cell-based microsystems at a level of $450K. Also included were two workshops, (1) MEMS for Military Applications, and (2) Multifunctional Materials for Energy Storage and Havesting. Army funds also incorporated two STTR Phase II projects on computational modeling of impact and penetration for $720K. The program also continued support for two HBCU projects in the amount of $175K to study the impact damage tolerance of hybrid composite materials. Approximately $700K has been allocated for the development of MEMS for rolling element bearings through OSD funds. Additional DoD funds in the amount of $ 340K were invested in the DEPSCoR program.

Interfaces - Because the field of solid mechanics has such wide applications to the design and the development of a multitude of Army materiel, there is strong coordination and interaction with a wide variety of Army laboratories and centers. Interactions with Army scientists and engineers occur through frequent visits to Army laboratories,

evaluations of proposals, suggestion of areas of research, determination of research relevance, jointly sponsored research and workshops, and at ad hoc meetings in specific technical areas. In addition, laboratory and center personnel interact with principal investigators at workshops and at professional society meetings. Each of the principal investigators supported by the program has visited at least one of the laboratories to interact with Army scientists. The primary laboratory interactions are with Aberdeen Proving Ground, ARDEC, Natick Soldier Systems, the Tank-Automotive Research, Development and Engineering Center, and the US Army Corps of Engineers Engineering Research and Development Center. There are strong interactions and collaborations with ARO programs in the Materials Science Division, Mathematical and Computer Sciences Division, and Biology Division through projects, workshops, and committees. Strong coordination is also maintained with other Government agencies such as the Office of Naval Research (ONR), Air Force Office of Scientific Research (AFOSR), National Science Foundation (NSF), NASA, and DoE. A particularly strong interface and interaction with ONR and AFOSR has been fostered through the Reliance process and the Sub-Scientific Planning Group in Solid and Structural Mechanics.

STRUCTURES AND DYNAMICS PROGRAM

Motivation - The interaction of inertial, elastic, impact, damping, and aerodynamic forces acting on armament systems, rotorcraft, missiles, and land vehicles is of fundamental importance to the design and construction of reliable, durable, and maintainable Army equipment with acceptable levels of personnel safety and comfort. As advanced weapons and mobility systems evolve to meet the demanding requirements of higher acceleration levels, greater loading rates, higher temperatures, and increased relative velocities among system components, Army scientists and engineers must devote greater attention to the development of effective, high quality military equipment that will withstand extreme battlefield conditions. Thus, designers must assure the integrity of structures and machine components through an understanding of the stress and deformation states that result from a variety of complex loading mechanisms in the static and dynamic regimes. This understanding can be attained through the development of sophisticated mathematical models and effective, efficient numerical solution techniques validated through extensive experimental investigations. Consequently, ARO supports fundamental research in structural mechanics of composite materials, gear dynamics, rotorcraft aeroelasticity, unmanned aerial vehicles (rotary wing and flapping wing aircraft), structural dynamics, structural control, simulation, and smart structures.

Structural Mechanics of Composite Materials - Engineers require refined theories of elastic structures and improved, precise, and efficacious analytical and numerical procedures to design complex structures, frequently fabricated from advanced composite materials, that can endure, without structural failure, repeated intense static and/or dynamic loading regimes. Many modern mechanical systems consist of combinations of rigid and deformable structural components that are light weight and strong, but sometimes brittle. Therefore, a highly relevant problem is that of the mathematical modeling of anisotropic and laminated composite beams, plates, and shells. Laminated

composite materials are prone to damage due to a variety of causes. One example is a tool, such as a wrench, dropped on a composite panel; it can cause delamination, breakage of reinforcement fibers, and matrix cracking. Since this damage can degrade the performance of the composite structure, it is necessary to be able to detect the presence of damage, its location, and its extent. Researchers are developing new techniques of performing structural health monitoring without inflicting additional damage in the structure. Refined mathematical models of damaged laminated structures are being formulated to predict the progress of damage and damage detection procedures based on strain indices and disturbances of wave propagation characteristics are being pursued, tested, and validated.

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The helicopter and automotive industries are today using composite materials in their new vehicles more frequently than previously because of their great strength, relatively light weight, and advantageous thermal and electrical conductivities. The experienced load spectrum in the Army application is extremely broad. Fiber reinforced composites are being studied for use in hingeless and bearingless helicopter rotor blades. These blades can be used with rotor hubs that are significantly less complicated and expensive than the mechanically complex hubs currently in use with articulated rotor blade systems. Aeroelastically tailored composite rotor blades offer significant potential for improved stability, reduced vibration, simplified hub design, and improved handling qualities of rotary wing vehicles. Advancements in each of these fundamental technical areas can lead to enhanced reliability, maintainability, personnel safety, and system performance. Development of new analytical tools to predict the complex dynamic behavior of these rotor systems is essential to the successful integration of tailored blade technology into next generation rotorcraft systems.

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As an example of timely research in this area, a current investigation is focused on the development of a new laminate theory to model laminated composites with multiple delaminations and build-in piezoelectric sensors. The newly developed theory will be validated with a comparison of numerical results with experimental measurements. In addition, attention will be placed on the development of strain based damage indices to integrate sensing data and to address the existence and severity of delamination in structural members. The researcher will also train an artificial back propagation neural network to simulate the vibration modal response and use the results obtained using this technique to detect delaminations – both through-the-width and internal.

In the course of the research, a comprehensive framework is being developed for characterizing and detecting delaminations in composite structures using built-in piezoelectric sensors. An improved laminate theory has been developed using a new layerwise deformation field description and two-way electromechanical coupling to characterize the presence of multiple discrete delaminations in composite laminates with piezoelectric sensors. The theory includes two types of non-linearities: (i) geometric non-linearity, caused by large deformation in the structure due to impact or low frequency high actuation by surface bonded actuators and (ii) the bi-modular effect of contact-impact, between the delaminated interfaces, during vibration. A damage indicator, based on layerwise in plane modal strains, is used to identify the presence of both discrete and overlapping delamination in composite plates. The delamination detection problem is formulated as an optimization problem with mixed type design variables using genetic algorithms and neural network. An artificial back propagation neural network is trained to simulate results from the finite element analysis and provide function approximations within the optimization procedure.

The significance of this work lies in the fact that delamination is a common form of damage that indicates the interlaminar failure of composite laminates and leads to a severe reduction in load carrying capability. Therefore, characterization, detection and quantification of delamination in composite structures are critical to the assessment of

structural integrity. A cost effective yet accurate analysis procedure will help reduce the number of expensive experiments, provide a physical understanding of the effect of damage on structural response and generate training data in the development of a framework for detection and characterization of damage in heterogeneous structures will help enhance the design, fabrication and reliable operation of such structural systems for use in military applications.

Structural Dynamics and Simulation - This area of activity is focused on ground vehicle and multi-body dynamics, structural damping, structural controls, and gear dynamics. Key problems are the determination of the transient and steady state response of structures that are subjected to forces such as gravity, damping, aerodynamic influences, and electric fields. Because of the magnitudes of the loads exerted on Army equipment and the need to reduce weight to enhance performance and range and to suppress noise, it is essential to include the deformation characteristics in the mathematical models developed to describe system behavior. Numerous large and complex mechanical systems used by or for the Army consist of interconnected multi-body structures, such as heavy machinery, wheeled/tracked military land vehicles, robotic equipment, machine tools, rotorcraft, vehicle engines, power transmissions, communication devices, and automatic weapons. To design such structures efficiently and effectively, kinematic and dynamic simulations of flexible multi-body systems on the basis of constrained nonlinear dynamics are required. In particular, recent advances in computers, graphics, and communication are undergirding recent developments in motion based simulators with computer generated imagery that interface vehicle dynamic models and their physical environments. Such computer simulations predict the kinematic and dynamic behavior of multi-body systems in considerable detail, providing sufficient data to study the influence of a variety of design parameters and to determine the detailed evaluations of concept performance capabilities. Examples of current research programs include the following:

To accelerate the computation of the dynamics of large scale systems, the development of model reduction techniques for large amplitude vibrations of complex non-linear structures based on non-linear modal analysis methodologies is in progress. Such models are used to predict effectively the vibrations of structural components and jointed assemblies and to assess fatigue life through the use of minimally sized models. Reduced models of non-linear structures are traditionally obtained using the modes of the associated linearized system as trial functions. *Linear modal analysis* of non-linear systems often yields undesirably large models, because non-removable modal interactions necessitate the retention of many linear modes. This results in slow modal convergence and, ultimately, expensive, inaccurate, or impractical models—as is the case for finite element-based models of rotorcraft blades. The *nonlinear modal analysis* developed in this project automatically incorporates into the reduced-order model the interactions between the linear system modes. Specifically, Galerkin numerical techniques have been developed for obtaining non-linear normal modes and carrying out non-linear modal-based model reduction for *strongly* non-linear systems over a large range of amplitudes. This allows one to construct the smallest possible system model for

the motions of interest, to a prescribed accuracy. The proper modal interactions are captured by choosing the trial functions to be the *non-linear normal modes* of the structure, rather than the linear ones. This novel approach yields reduced order models that account for the effects of the eliminated coordinates through an analytically rigorous, yet practical, methodology. Due to its systematic nature, this method may be automated such that little additional analytical work is necessary for each new nonlinear structure. It may also be interfaced with finite element codes, and thus applied to industrial structures of arbitrary size and complexity. Rotorcraft, ground vehicles, and other structural systems used by the U.S. Army typically exhibit non-linearities due to large displacements, contact, friction, pre-load, and clearance. These have a substantial, qualitative influence on structural response and the attendant vibration, noise and reliability. In many cases, model size and complexity prohibit accurate analysis. With the non-linear modal analysis approach, a complex non-linear system can be reduced to a minimally sized model with just a few essential degrees of freedom. This reduced order model is optimal since the characteristic motions of the original system are inherently captured by the corresponding non-linear normal mode model. Consequently, these reduced-order models will facilitate high fidelity simulation of both existing and proposed designs. Ultimately, the approach may be integrated into analysis packages, such as comprehensive rotorcraft analysis codes or the ground vehicle simulation software developed by the U.S. Army funded Automotive Research Center at the University of Michigan, to yield faster, more accurate models and hasten the design cycle for rotorcraft and ground vehicles.

Another research project is aimed at developing a comprehensive numerical simulation capability of noise and vibration and its reduction in rotorcraft using partial span actively controlled trailing edge flaps, implemented in a single or dual flap configuration. A novel feature of the code being developed is that both the simulation of the vibration and the simulation of noise generation are based on the same aeroelastic model, and thus blade dynamics and flexibility are incorporated in the acoustic portion of the simulation. Furthermore, the actively controlled flaps are actuated using adaptive materials based actuation. This research is motivated by the experimental evidence obtained in wind tunnel and flight tests that has shown that when vibrations are reduced using active control in many cases noise levels tend to increase and vice versa. The physical reasons for this behavior are not well understood and the overall objective of the research project is to develop a fundamental understanding for this problem, through numerical simulation, and use it to achieve simultaneous noise and vibration reduction. The specific objectives of the project are to develop an aeroelastic/acoustic simulation capability for a rotor that can be used to study vibration reduction using actively controlled flaps (ACF), while keeping track of the noise generated; to identify the reasons why increased noise levels often accompany vibration reduction using active control; to develop objective functions and control laws based on the dual flap configuration that guarantee simultaneous vibration and reduction using a dual ACF system.

The research in progress is based on the development of a sophisticated simulation

capability that can model active control of vibration; unsteady aerodynamic pressure distribution on the blade surface and noise generated by the pressure distribution, these three ingredients mentioned are based upon a common aeroelastic blade model. This requires several modifications and enhancements in our existing simulation code. For example, the currently used aerodynamic model consists of a combination of three important components: (1) an unsteady, compressible, two-dimensional model for the blade flap combination that accounts for variations in oncoming velocity, (2) a free-wake model , and (3) dynamic stall model that is identical to the ONERA dynamic stall model. For vibration reduction only the span-wise pressure distribution is needed. However, for noise calculations the chordwise pressure distribution is also needed. Therefore, the unsteady aerodynamic model in the researcher's simulation code was extended so that it generates chord-wise unsteady aerodynamic loading from a combination of two-dimensional time domain compressible aerodynamics for the blade/flap combination (attached flow), ONERA dynamic stall model (separated flow), and free wake for 3D inflow distribution. This unsteady pressure distribution is required in order to obtain acoustic information from an acoustic code.

The Army significance of this project lies in the fact that vibrations lead to fatigue damage of structural components, increased maintenance costs, pilot fatigue and discomfort and reduced effectiveness of weapon systems. Noise limits the capability of the helicopter to operate in a stealthy manner. Clearly, simultaneous vibration and noise reduction will bring enormous benefits.

Smart Structures - A smart structure is defined to be a structure that contains embedded sensors and actuators with associated control system capabilities enabling it to respond in real time or nearly real time to external stimuli in proportion to their intensity to compensate for undesired effects or to enhance desired effects. The application of the smart structure concept offers the potential for the development of a new series of structural systems that may find application in modern rotorcraft, land vehicles, weapons systems, aircraft, electromagnetic antenna systems, submarines, spacecraft, and industrial machinery. To realize the promise of such active structures, additional research is required into the fundamental understanding of how they function and how they can be controlled. Hence, engineers and designers must know how to create the next generation of active materials that can serve as effective sensors and actuators, how to express appropriate constitutive equations, how to derive their equations of motion, how to design efficacious controllers, etc. This knowledge will permit Army engineers to suppress the vibrations in machine gun barrels and rotorcraft structural components; augment aeromechanical stability; enhance rotorcraft handling and maneuverability qualities through the change of a rotor blade's camber; reduce blade-vortex interaction noise levels in rotorcraft; and detect structural damage, such as material fracture, debonding, and delamination.

The most prominent actuation techniques suggested for smart structures are based on the properties of piezoelectric ceramics and films, shape memory alloys (such as nitinol), electrorheological fluids, electrostrictive materials, and magnetostrictive materials (such

as terfenol-d). New active materials that deliver superior levels of force or stroke for actuation purposes have recently been developed. These include single crystal relaxor ferroelectric materials and high strain ferromagnetic shape memory alloys. Such materials may help engineers to design and produce, for example, active twist helicopter rotor blades or effective trailing edge flaps on helicopter rotor blades. The benefits of these are that vibration amplitudes will be diminished, blade-vortex interaction noise reduced, and rotor system lift increased. However, it may prove necessary to devise hybrid actuators formed by combining the properties of two or more actuating substances or to consider optimized actuator configurations that deliver greater force or displacement levels.

As an example of research in this area, researchers are investigating new, effective ways of using embedded anisotropic piezoelectric actuation in helicopter rotor blades to improve blade response, diminish vibratory hub loads, and enhance rotor performance. The project objectives are to develop active aeroelastic analysis capabilities that account for the three-dimensional electroelasticity effects of anisotropic piezocomposite actuators embedded in the blade composite construction; explore new ways of integral blade actuation and active blade aeroelastic tailoring to minimize hub vibratory loads; and experimentally bench test few selected actuation concepts identified from numerical studies. Cross-sectional analysis is being performed since it carries all the information and corresponding degrees of freedom necessary to excite different deformation states of the three-dimensional blade. To solve the general problem of arbitrary geometry and material distribution, no closed-form solution is expected and the finite-element discretization of the cross section will be used. The problem can be reduced to a one-dimensional blade analysis, in which the effects of the active materials will be carried to a geometrically exact beam formulation, which is the natural result from the asymptotically correct condensation of the original three-dimensional problem. In this framework, one then deals with large displacements and rotations while the blade still undergoes small strains, and no ordering scheme or any other type of approximation is needed *a priori*. Throughout this study, close contact with the Army Research Laboratory/Vehicles Technology Directorate will be pursued. Lessons learned from the development of the NASA/Army/MIT Active Twist Rotor program and the investigator's involvement with the next-generation Army's Advanced Active Twist Rotor program will directly contribute to the development of each of the above phases of this project.

Rotorcraft vibration and noise reduction, as well as increasing rotor performance and maneuverability, continue to be primary concerns for the military (and civilian) helicopter enterprise. The most promising solutions are based on electromechanical approaches exploiting active material actuators. Among those, the integral twist actuation concept provides redundancy in operation, does not increase the profile drag of the blade (like discrete flap concepts), and once the actuators are embedded in the composite blade they become part of the load bearing structure, making the active blade a truly integrated multifunctional structure. The integral twist actuation concept using active fiber composites has been tested in the wind tunnel and the vibration reduction capabilities are outstanding. This project will provide the necessary dynamics modeling

to explore and benchmark anisotropic actuation mechanisms for future design of active rotor blades. This will greatly enhance the understanding and potential application capabilities to support future developments of active twist rotors at the Army's Vehicle Technology Center and the Army's Aeroflightdynamics Directorate.

Investment - During FY04, a total of about $12.45 million from all sources was committed to the support of research in the Structures and Dynamics Program. Of this amount, about $1.15 million were invested in twenty-one single investigator projects, which were focused on structural dynamics, smart structures, and structural control research. Under the URI program, there was one instrumentation grant ($0.25M). This DURIP award furnished funds to purchase a basic main rotor test stand for the active control of vibration and noise in helicopter rotors. This instrumentation complements an ARO single investigator project that is concerned with active control for simultaneous noise and vibration reduction in rotorcraft employing active material based actuation. This activity is developing control laws for simultaneous vibration and noise reduction using an actively controlled dual flap system. The program also included approximately $7.8 million of DARPA funds that supported research projects focused on investigations of the development of a swashplateless helicopter rotor system, relaxor ferroelectric materials for adaptive structures applications, where enhanced stroke authority is required., and exoskeletons for human performance augmentation. Applications of the actuators developed in the projects are foreseen in rotorcraft, fixed wing aircraft, some naval systems, and soldier support systems. The remaining $3.25 million were invested in the support of one PECASE award ($0.1M), two STTR program Phase 2 awards ($0.78M), one MURI program ($0.45M), and set-aside funds from ASAALT and OSD ($1.92M).

Interfaces - There is an important interaction between the Structural Mechanics Branch and the Army laboratory scientists and engineers. The latter experts provide valuable assessment of the technical quality and Army relevance of research proposals received at the ARO. They exert considerable influence on the shaping of the Branch's research programs. For example, the needs and programs at AMCOM's Aeroflightdynamics and Aviation Applied Technology RDEC's, and ARL's Vehicle Technology Directorate strongly motivate the selection of research projects supported in the rotorcraft dynamics program and the smart structures programs. Army specialists at AMCOM, TARDEC, ARDEC, Natick RDEC, and ARL are instrumental in identifying the highly relevant areas to be followed in the structural mechanics of composite materials and in the area of vibrations, stability, and control. Frequent contacts are maintained with ONR, AFOSR, DARPA, BMDO, and the National Science Foundation through inter-agency meetings, reviews, and workshops to exchange program information, collaborations on evaluation teams, and meetings at technical conferences.

B. Thrusts and Trends/Workpackages

PROPULSION AND ENERGETICS PROGRAM

Engine Combustion - The major thrust in the Propulsion and Energetics Program is clearly in the diesel engine combustion area. The objective is to determine and quantify those factors that control engine efficiency and performance. With the increasing emphasis on high-efficiency/high-temperature engine development, a key goal is the accurate determination of temporally and spatially resolved fuel injection/atomization, autoignition, turbulent, heterogeneous combustion, and heat transfer. Increased attention is being given to understanding the mechanics of atomization in high-pressure sprays and ignition processes.

Gun and Missile Propulsion/Energetic Materials Hazards - Major emphasis is being given to understanding transient events. In both conventional and advanced gun and missile propulsion systems employing chemical energy, the initial ignition event is critical, as is the subsequent energy gain/loss leading to propagation/quench of reaction. This is also true in the inadvertent ignition of propellants due to shock, impact, or electrostatic discharge. This is a highly coupled flow, chemistry, and heat transfer problem requiring state-of-the-art instrumentation and computational capabilities. Areas of major emphasis include ignition dynamics, flame spread, and combustion-material coupling. An additional emphasis is on the development and characterization of novel energetic materials based on nanotechnology.

FLUID DYNAMICS PROGRAM

Flow separation plays an important role in limiting the performance of many Army systems. Unsteady separation of boundary-layer fluid on the suction side of rotorcraft blades leads to dynamic stall on the retreating side of the rotor disk, with an attendant loss of lift and large negative pitching moment. Dynamic stall can be thought of as the pacing technical item inhibiting the development of agile supermanueverable rotorcraft. Flight regimes directly affected by this phenomenon include air combat, terrain following the nap-of-the-earth, and "shoot and scoot." Missile and projectile base and afterbody flows often involve flow separation caused by control surfaces, shock waves, or discontinuous changes in body contour. Clearly, a thorough understanding of the various fluid dynamic mechanisms underlying flow separation can be used to tremendous advantage in the design of future Army systems, and the trend in the fluid dynamics program is to apply this fundamental knowledge to control this phenomenon.

Accurate performance prediction of Army missiles and projectiles requires the ability to accurately predict the flowfield in the base region of these devices. While the modern techniques of computational fluid dynamics have made great contributions in this area, they are limited by the lack of accurate nonequilibrium turbulence models. It is difficult to formulate such models even for situations in which the flowfield has been well documented. In the case of missiles and projectiles operating at transonic and supersonic speeds, quantitative experimental measurements of the base-region flow are exceedingly difficult to perform accurately, and the task of the development and selection of adequate turbulence models is extremely challenging.

SOLID MECHANICS PROGRAM

Heterogeneous Systems - A thrust area of particular importance to the Army, in the solid mechanics field, is in the area of multi-constituent systems and materials. Any system or material can be considered heterogeneous at some spatial scale, and the properties of and interaction between constituents are critical. The effect constitutive relations, load transfer, interface, and interphase on failure mechanism determination, assessment, and damage play an important role in the overall structural and mechanical performance of heterogeneous systems. Particular emphasis is placed on complex and extreme loading environments, where the coupling between different physical scales (temporal and spatial) and overall material response is essential for the design of new and significantly improved Army equipment. Typical areas requiring emphasis are the identification, control, and scaling of multi-scale mechanisms, tailoring of hybrid material systems for the development of new structural and mechanical systems, and development of computational tools and multi-axial experiments pertaining to damage progression and failure evolution.

Impact, Penetration, and Shock - Another major thrust is the determination of impact and penetration processes and shock wave propagation in heterogeneous structures with special focus on the high strain rate phenomena and resulting material failure sequences. Accurate and detailed physical understanding of the processes needs to be obtained and predicted. Full-field computational models and experiments are needed to provide predictions and information that cannot be obtained from live-fire tests or current simulations and to account for variability related to what-if failure scenarios. Innovative numerical and experimental techniques are needed to address current scientific challenges and barriers pertaining to the performance and the development of new and significantly better armor and anti-armor systems on appropriate spatial and temporal scales.

STRUCTURES AND DYNAMICS PROGRAM

Nano-scale technologies offer attractive possibilities of developing innovative structural damping materials that exhibit novel physical properties. Recent ARO supported activity has been directed toward the development of novel elastomeric composites through distributing carbon nano-tubes within the host polymer. The first phase of this work is concerned with the development of a constitutive model to describe the mechanism of energy dissipation for polymeric composites reinforced by single walled carbon nano-tubes. Due to the high strength of carbon-carbon bonds and their nearly perfect lattice structure, it has been shown that by using small fractions of carbon nano-tubes as a reinforcing mechanism, ultra-light weight structural composites with significant improvements in elastic modulus can be obtained. Prior to this time, the damping characteristics of elastomeric composites with embedded carbon nano-tubes have not been explored in any detail. This investigation has demonstrated that maximum damping

effects can be obtained within a certain strain range and that maximum damping effects increase with the magnitude of critical bonding stress and nano-tube volume ratio. Since the choice of polymeric matrix material, nano-tube surface treatment, and composite manufacturing process can have significant effects on the critical bonding stress, the possibility exists for achieving optimal structural damping performance through the design of different nano-tube reinforced composites

Conventional numerical methods for solving problems of viscoelastic solid deformation generally do not include any form of error estimation. Research in progress on quasi-static linear viscoelasticity has developed new calculable error estimates for finite element methods that have subsequently been used to produce adaptive finite element schemes. Models developed to date in collaboration with the ARL/Vehicle Technology Directorate have been based on hereditary integral formulations of viscoelasticity. These will be extended to formulations that involve internal variables. Dynamic problems have highly structured solution and error behavior in that information is propagated along preferred characteristic directions. Classical error-norm based adaptivity is not sufficiently sensitive to detect this and usually results in meshes that are excessively refined in the wrong place – leading to a significant over-demand of computational effort. The technique and algorithm under development are based on a modern method of error estimation that is sensitive to the underlying error structure and is able to adapt meshes and time steps in precisely the way required. These points are important because, as engineers require effective and accurate simulation of increasingly complex physical systems, it becomes essential for the software tools to be both efficient and reliable. Although many commercial finite element codes have a viscoelastic capability, they rarely allow for adaptivity and reliable error control in space-time (e.g., ABAQUS). This project is laying foundations for that theory along with prototype software.

Sliding friction between the gear teeth is considered to be a key source of excitation for structure borne noise in rotorcraft drivetrain applications. The primary focus of research on the effects of sliding friction in rotorcraft geared systems is to study its role through computational, analytical and experimental approaches. This project is concerned with the development of a realistic lumped parameter model for gear dynamics that incorporates accurate representations of sliding friction, time-varying mesh stiffness, and load sharing between meshing tooth pairs. This is coupled with an experimental validation of the system model and the study of various scenarios using the lumped parameter system model as a research/simulation tool. This effort is leading to the development of engineering knowledge, design guidelines, analytical tools, and computer codes to assist in evaluation of new gear designs. In particular, a new linear time-varying lumped parameter system model (LTV) for a spur gear pair has been developed. This model includes: (1) Accurate representation of tooth contact and spatial variation of tooth mesh stiffness obtained using a finite element/contact mechanics formulation. This aspect is very important to account for the unequal load sharing between the multiple pairs of teeth in contact. (2) A Coulomb friction model for sliding resistance. (3) A multi-degree of freedom model considering both torsional and translational dynamics of the gear pair. In addition, a model for the helical gear is in progress. One key question

that is answered by the multi-degree of freedom model is that sliding friction is the source of critical oscillations of the bearings in the off-line of action direction. The bearing reactions in the line of action direction are dominated by the normal tooth loads, while in the off-line of action direction frictional effects are important. This system model is a precursor to a lumped representation of a helical gear pair that additionally exhibits coupling with axial motions due to axial force shuttling phenomenon. Overall, the sliding friction has an effect of increasing the higher harmonics of the dynamic transmission error, particularly at high torque levels, for a single degree of freedom model for a NASA-ART spur gear pair. This is a comprehensive study aimed at incorporating all aspects of friction in gear dynamic models and vibration control schemes. Many dynamic phenomena that emerge due to interactions between parametric variations (time-varying mesh stiffness) and non-linear characteristics, such as super-harmonic resonance, unstable regimes, multiple solutions, and angular modulation will be predicted. The results of this study are expected to greatly enhance the current state-of-the-art in gearbox noise and vibration and lead to improved design guidelines that will benefit the Army Research Labs (at NASA Glenn) and the rotorcraft industry in general. Plans are underway to conduct experimental studies at ARL/NASA Glenn and to apply the knowledge generated in collaboration with Sikorsky. Also, our analyses are expected to explain some of the empirical data.

III. SPECIAL PROGRAMS

A. Multidisciplinary University Research Initiative (MURI) Program

Hybrid Biomechanical Devices

This program is developing biomechanical interfaces for functioning cell-based microsystems. The research team includes Caltech, Johns Hopkins University, Northwestern, and the University of California at Santa Barbara. The innovative program was seeded by the work of the principal investigator, chemist Milan Mrksich, who had demonstrated that power densities from beating heart cell (cardiomyocyte) cultures would be sufficient to drive MEMS (microelectromechanical system) devices. Prospective applications include meeting Army needs for chemical and biological agent detection and identification, development of active coatings for camouflage and signature reduction, and energy extraction from the environment. Creating successful devices utilizing such technology requires a detailed attention to the means of coupling between the cell and the mechanical element. Thus, the first aim of the program is to develop a test bed for interfacing mechanical actuation with cellular material, starting with elemental devices to measure the spatial distribution of traction forces, exhibited by a cell on its substrate. These experiments will evolve into a sophisticated scanned force-sensing testbed to study single cell mechanical interactions. This platform will then become the workhorse for a detailed understanding of the mechanical signatures for cellular activities, mechanical actuation of cell behavior, and fatigue and failure of the

cell biomechanical system. Finally, the team will investigate specific configurations for tasks such as CBW agent detection, active coatings, and energy extraction.

Micro Hovering Aerial Vehicles with an Invertebrate Vision Inspired Navigation System

Small rotary or flapping wing unmanned aerial vehicles (UAVs) have significant advantages over their fixed wing counterparts when the vehicle is required to hover or maneuver in, for example, building interiors, tunnels and caves. They must be extremely rugged to withstand harsh gust environments, endure obstacle collisions, operate in all types of weather, perform stationary hover and autonomously navigate in tightly constrained environments. To improve rotor/wing performance in the low Reynolds number aerodynamic regime, biomimetic unsteady mechanisms for pitching and plunging motions must be investigated. These vehicles must be capable of performing highly maneuverable and hovering flight to avoid collisions with obstacles and to maneuver effectively in confined spaces. To achieve this autonomous performance, the micro-aerial vehicle must possess a navigational control capability, which possibly could be realized through incorporation of invertebrate vision and the compound eye. Research proposals in this technology are currently under evaluation in the latest MURI solicitation. Areas of research concentration for aerial vehicles include: (1) the understanding of the complex aerodynamic flow behavior at low Reynolds number [laminar flow, viscous drag, delayed stall, rotational circulation, wake capture, flow separation, vortex control]; (2) development of a mechanically simpler swashplateless rotor or flapping wing system that provides the pitching and rolling moments necessary for primary control, vibration reduction, and stability augmentation; (3) reconfigurable geometries such as adaptive smart skins, variable geometry rotors, etc. to improve performance and maneuverability; (4) robust insect-like navigation and flight control algorithms for obstacle avoidance and autonomous operation; (5) techniques to predict fluid-structure-control interaction; (6) active control of noise through smart-morphing of primary and auxiliary surfaces to minimize noise, reducing detectability; and (7) schemes for multiple vehicle coordination and mission execution (swarms or teams, multiple agents). Vision research to be integrated with the micro-aerial vehicle should be focused on acquiring a leap-ahead understanding of relevant concepts of design and information coding principles at the fundamental level for the biological patterns of activity supporting compound eye system function in response to visual stimuli. Included, for example, might be studies of system integrative properties as they relate to any spatial and temporal nonlinearity in sensory information processing for movement detection, and how nature's optimization of the principles involved might be exploited in engineered systems for advanced image processing. Micro hovering aerial vehicles will provide exceptional capabilities for reconnaissance, covert imaging, urban intelligence gathering, biological and chemical agent detection, battlefield surveillance, targeting, minefield detection, early warning, communication, troop location and maneuver, terrain mapping, environmental prediction, and damage assessments. Deployed in groups, with each vehicle equipped with a different kind of sensor, they will provide a robust capability for communication, command, and control. Besides directly impacting micro-aerial vehicle navigation, robotics, surveillance,

situation awareness, and stealth and camouflage defeat, it is likely that these studies will also have substantial impact in the areas of target acquisition capabilities for effective missile defense.

Lightweight Damage Tolerant Structures

A multidisciplinary program with emphasis on aspects of materials, mechanics, mathematics, and computational sciences was initiated in FY96. The objective of this program is to develop the underpinnings necessary for the design of future armor systems that will be severely constrained by limitations of weight and space with significantly improved performance and durability. The program resides in the Materials Division with strong support from the Mechanics Branch. Purdue University and the University of California at San Diego are supported by this effort. One of the key thrusts of the program is to develop predictive models, based on benchmark experiments, analytical formulations, and computational analyses, of the spatial and temporal evolution of damage in structures under extreme loading conditions. The models will account for phenomena at various scales, such that it is physically meaningful and be computationally efficient for applications, such that new systems can be designed and their performance can be optimized.

Nano-Engineered Energetic Materials

A new, multi-university effort was initiated in late Fiscal Year 2004. The lead institution is Pennsylvania State University, with participation by the University of Illinois, Urbana-Champaign, and the University of Southern California. The overall goal is to engineer multi-dimensional, nanoscale energetic materials systems whose energy release can be controlled in terms of its type, rate, spatial distribution, and temporal history. This will be achieved through the manipulation of individual atoms and molecules and the control of their assembly into a large-scale bulk energetic material. The possibility exists to build large-scale energetic materials with a very high degree of uniformity (few/no defects, perfect crystalline structure, composites with molecularly engineered uniformity, laminated composites with structures built molecularly controlled and selectable layers - - no stirring, mixing - - all done through self-assembly). It is also possible to embed molecular scale devices within the energetic matrix (embedded smart devices and sensors). Specific topics under investigation are: (1) The development of the chemistry, physics and materials science of nanoscale energetic material, focusing on those processes that lead to well ordered structures, e.g. self-assembly, vapor deposition, etc.; (2) Computational methods to assess the reactivity of candidate structures and to predict the stability of the energetic material structure, to both hazards (shock, spark, etc.) and to long-term degradation. These computations will also provide guidance to and receive validation from the experimental aspects of the program, specifically the formulation and characterization activities. (3) The development of experimental methods of characterizing nanoenergetic structures to verify structure and performance. This includes development of techniques capable of the determination of the three-dimensional structure of the nanoscale assembly and the orientation and bonding of the

constituents.

B. Defense University Initiative in Nanotechnology (DURINT)

Processing and Behavior of Nanoenergetic Materials

In 2001 a new, multiyear research effort was initiated under the Defense University Initiative in Nanotechnology (DURINT) program. The program is focused on the development of nano-scale energetic materials. In contrast with current propellant and explosive formulations, which are characterized by micron-sized particulates, the new materials will have nanometer scale structure. It is expected that this will lead to dramatic gains in performance.

The program is a multi-university collaboration, headed by Professor Michael Zachariah, now at the University of Maryland, formerly of the University of Minnesota, with participation by the University of Delaware, Oklahoma State University, and the South Dakota School of Mines and Technology. The research is exploring the development, characterization, and reaction kinetics of the new, novel class of energetic materials, prepared on the nano-scale.

Specific research thrusts for this program include developing new methods for production of nanoparticles and passivating their surfaces. These include developing new sol-gel methods for generation of nanostructured materials with emphasis on energy release and the flow/chemistry/aerosol modeling of particle formation from thermal plasmas. New nanoparticle characterization approaches are being developed based on Laser Induced Breakdown Spectroscopy (LIBS), single-particle mass spectrometry and calorimetric studies of thermochemistry of nanoparticles and nanostructures. Studies of reactivity include determination of nanoparticle oxidation kinetics, characterization of energy release using fast spectroscopic techniques, and the measurement of solid-solid exothermic reactions. The experimental work is supported by the development of computational chemistry/physics models of nanostructures.

C. DARPA Program on Micro-Active Flow Control

Over the last decade the same microfabrication techniques originally developed for the production of electronic integrated circuits have been used to develop miniature mechanical devices (known as Micro Electrical Mechanical Systems, or MEMS). In fluid dynamics applications, the small size and mass of these devices have enabled the production of sensors and actuators with outstanding temporal and spatial bandwidth, enabling multiple applications for flow control: here the philosophy is the insertion of very small control forces at crucial spatial and temporal locations in order to obtain significant changes in system performance. The focus of this DARPA-funded, ARO-managed program is to apply these techniques to a variety of Army systems in order to assess their technical, operational, and economic feasibility: systems under consideration include gun-launched grenades, tilt-rotor and conventional helicopters, and

turbomachines. During the last year much of the emphasis of this program was on large-scale demonstrations of these technologies on Army systems.

D. DARPA Program on Helicopter Quieting

This new program has the goal of revolutionizing the current method of designing helicopter rotor blades thereby enabling the creation of novel rotor blade designs that can dramatically reduce the acoustic signature of a helicopter without sacrificing flight performance. The focus of the first phase of this program is to create a physics-based design tool that can predict performance regardless of blade shape. To accomplish this will require the development and implementation of advanced turbulence modeling tools, such as large eddy simulation (LES) , LES-hybrid schemes, and/or detached eddy simulation. This would enable the virtual testing of a wide variety of designs from unusual tips to movable flaps or slats or any other innovative design idea. Subsequent phases of the program are anticipated to concentrate on developing, testing, and transitioning an advanced low-noise blade design developed using the new design tools.

E. DARPA Program on Exoskeletons for Human Performance Augmentation

In addition to an exoskeleton project underway at the University of California at Berkeley, ARO is also monitoring another important exoskeleton research activity at the Sarcos Research Corporation in Salt Lake City, UT. The prime objective of the Sarcos "Wearable Energetically Autonomous Robot (WEAR)" project is to develop and demonstrate a new class of military systems designed to extend the capabilities of ground forces, by enhancing the performance of the individual soldier. For this purpose, a series of systems are being developed, including: (1) Lower Extremity Exoskeleton (LEX) functional mock-up, a LEX prototype (LEX-1) and a LEX pre-production system and (2) Full Body (FB) Exoskeleton functional mock-up, FB prototype and a FB pre-production system. A series of key technologies and sub-systems is being developed to meet its system level targets. The objectives of the related sub-projects are to develop: (1) compact, robust, lightweight, kinematically and dynamically compatible structures (links and actuated joints); (2) interfaces between the machine and the operator's soft tissues that are safe, comfortable, and that allow easy and rapid donning and doffing; (3) a new class of direct energy conversion power source and actuators that can efficiently use combustible fuels to achieve high energy and power density, high force and speed, large range of motion, small overall size and mass, servo-quality movement and force control ability, with low friction and stiction, and low quiescent power use; and (4) technologies that allow the new power sources to operate using Alternative Fuels (AF) available on the battlefield, such as JP-8 (the primary logistic fuel adopted by the US army), diesel, and JP-5. The efficient mobility of legged machines over rugged terrain and the ability of WEAR to increase the effective stamina, mobility, speed and strength of the user will significantly enhance the lethality and survivability of the dismounted warfighter and improve operation parameters in missions such as hostage rescue, building clearing, medical evacuation, reconnaissance and intelligence gathering. More specifically, WEAR will augment the performance of the warfighter by:

- Increasing it's ability to deliver heavy payloads and equipment over extended ranges, or for long mission duration, while reducing the operator's fatigue and risk of injuries; and by
- Increasing the operator's mobility while: (i) carrying protective covers such as ballistic armor and blast shields, heat or flame protection shields, chemicals, radiation and biological protective gear; (ii) transporting wounded personnel; (iii) transporting heavy weaponry and munitions; (iv) working on heavy machinery; and (v) carrying loads for fellow squad members (thus freeing them for defensive/aggressive action), and others.

Research is focused on the development of system configuration concepts supported by animation and physics-based dynamic simulation of various notional systems. These analysis are, for example, used to estimate: (i) joint torque versus joint speed locus; (ii) structural loads and stresses; (iii) control sensor flexure configuration; (iv) performance and control of new hydraulic supplies and servo-valves; and (v) exoskeleton control strategies. Sarcos engineers have developed passive exoskeleton structures (kinematic mock-ups) having increasing levels of similarity to the actual WEAR systems. These devices have been used to evaluate joint kinematics configurations, structural link configurations and actuator placement and mass distribution, soft tissue and foot interfaces, ergonomics of the control interfaces and of the entire system for donning, doffing, and the general impact of the system on the user's mobility.

F. MDA Program on Missile Signatures and Aerothermo-Chemistry

The focus of a group of ARO-managed, MDA-funded programs is the development of predictive models for the ultraviolet, visible, and infrared radiation from hypersonic missile flowfields and rocket exhaust plumes.

Computational simulation of a hypersonic flowfield in the upper atmosphere requires that the non-equilibrium shock wave structure be accurately computed. The conventional Navier-Stokes equations are incapable of doing this, because essential physics is missing from their formulation. A major objective of this research is the development of new codes for computing flowfield radiation. Results indicate that by using improved physical models for critical processes, reliable computations may be made up to 90 kilometers altitude using continuum techniques. To cover the higher altitude regime, Monte Carlo flow calculation methods are being incorporated. The combination of approaches will provide the capability for ground level-to-space flowfield computation. The research effort has also focused on assessment and correction of critical deficiencies in the prediction of ultraviolet radiation from hypersonic flowfields. Of particular importance is the inclusion of non-equilibrium energy exchange rates within rotation, vibration, and electronic states. Molecular dynamics calculations are being used to predict collisional excitation processes. In particular the effect of rotational excitation under non-equilibrium conditions is being studied for both air and exhaust plume species.

With increasing emphasis being placed on theater missile defense, the MDA program has been expanded to cover the issues associated with hypersonic interceptor operation at lower altitudes. In this regime, there are major unresolved issues in the stability of flows over hypersonic vehicles, and the appropriate rates of convective heat transfer. Additionally, the high temperatures generated in the flow can lead to sensor degradation by increased background radiance levels and optical distortions. Advanced computational fluid dynamic models are being developed to handle the hypersonic, three-dimensional flows, with detailed chemistry. In June 2003, the Dual-Mode Bow Shock Interaction (DEBI) was launched from Wallops Flight Facility, Virginia. That experiment obtained data on the short-wave infrared emissions from a hypersonic shock layer as a function of altitude. The analysis of that data, in progress, will yield new understanding of the physics of hypersonic flows.

G. MDA Program on Novel Kinematic Structures

All branches of the U.S. military continue to have needs for vibration isolation, vibration absorption, precision pointing, and tracking. Ideally, all of these tasks should be performed in a fault tolerant manner. Professors John McInroy and Jerry Hamann at the University of Wyoming have developed a six-legged platform, or hexapod, that is capable of performing simultaneous vibration isolation and precision pointing in a fault tolerant manner. This research has three main objectives: (1) to extend previously developed modeling, control, and fault tolerance techniques developed from the current six degree-of-freedom hexapod to general mounting problems; (2) to seek alternative designs for precision parallel kinematic machine joints; and (3) to focus efforts on three applications:

1. Laser weapons and target illumination mounting, which requires ultra-precise acquisition, pointing, and tracking, in addition to absorption of vibrations generated by the laser, isolation from vibrations onboard the host vehicle, and (depending on the implementation) lifting of large static weight.

2. Reconnaissance camera mounting, which requires isolation from host vibrations, absorption of local machine vibrations (especially if cryogenically cooled), and two degree-of-freedom open loop fine pointing.

3. Helicopter rotor mounting, which requires absorption of vibrations, large load capabilities in several directions, resilience to constant fatigue loads, and coarse two-axis tilts for redundant emergency operation.

This project's research activities are aimed at drastically reducing the mechanical complexity of parallel kinematic machines. For instance, to reduce fatigue and manufacturing costs, the intricate spherical joints will be redesigned. The mechanical complexity will be supplanted by sophisticated mechanical and control design, optimized to meet a variety of criteria (reliability, control bandwidth, thermal range, strength). By

developing general methods of designing flexible parallel kinematic machines with desired kinematic, dynamic, and control properties, a new class of machines with thermal, loading, and cost advantages is likely to result.

IV. SCIENTIFIC ACCOMPLISHMENTS

Several examples of many scientific accomplishments from the 2004 Mechanical Sciences Program are described below:

Simulation of Supersonic Base Flows: Numerical Investigations Using DNS, LES, and URANS
H. Fasel, University of Arizona

Measurements have shown that as much as 35% of the total drag on a supersonic projectile can be attributed to the flow within the base region. Accurate prediction of this compressible flowfield using the Reynolds averaged Navier-Stokes equations and the tools of computational fluid mechanics is hampered by the lack of an adequate turbulence model. In the current research, direct numerical simulation of the flow behind an axisymmetric Mach 2.46 projectile have been performed at a Reynolds number based on diameter of 100,000. These computations were conducted on a grid with 57×10^6 grid points, requiring approximately 24 GB of memory. Instantaneous end-views of local Mach number from these calculations are compared with visualizations of the experiments by Dutton and co-workers at the University of Illinois at Urbana-Champaign (also performed under ARO support) in figure 1.
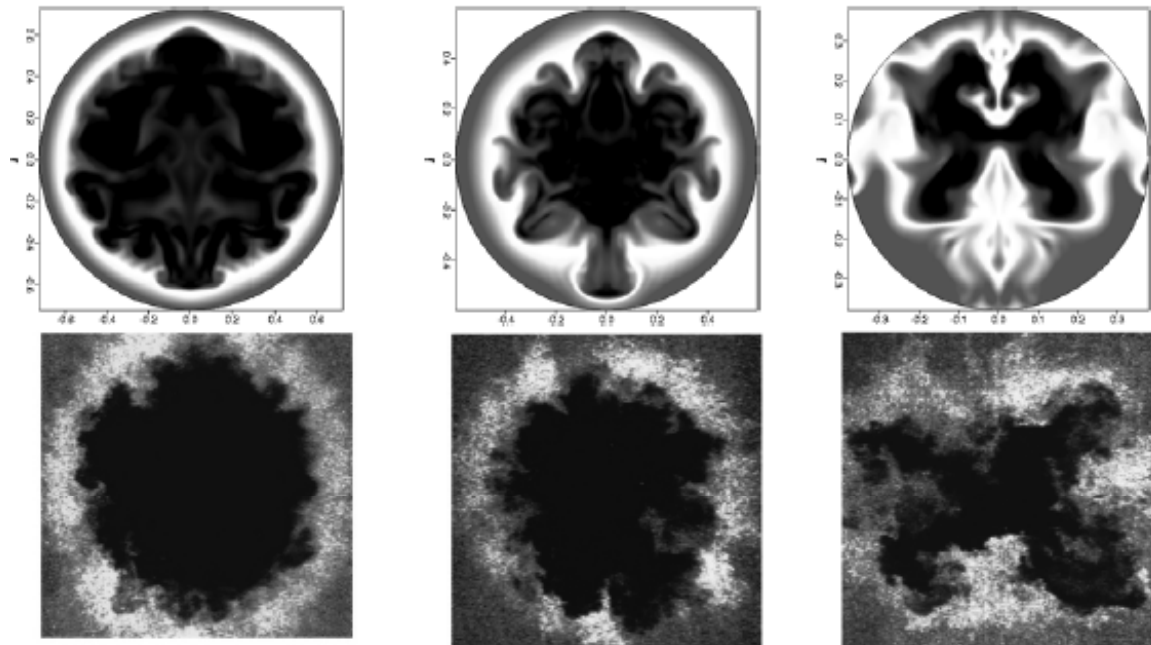
Figure 1. End-views of contours of instantaneous local Mach number (top) at Re_D=100,000 and M=2.46, compared with visualizations from experiment by Bourdon and Dutton (bottom) at Re_D=3,300,000 and

M=2.46; locations "C", "D", and "E" are shown from left to right.

In spite of the significant difference in Reynolds number, the resemblance is remarkable. Just upstream of the mean reattachment (here z = 3.5), 12-14 structures can be detected in the shear layer, in good agreement with the typical number of 10-14 observed in the experiment at the same location ("C"). The streamwise structures appear to undergo an amalgamation in downstream direction, evidenced by a decreasing number of structures further downstream. At z = 6.5 (location "E" in the experiments), in the developing wake, only four streamwise structures are visible, as was also observed in the experiments. Furthermore, the mushroom-like shape of the structures, indicating the existence of instantaneous longitudinal structures, is very similar to the observations by Bourdon and Dutton. These observations leads to the conjecture that similar instability mechanisms are present at ReD = 100,000 as in the experiments for much larger Reynolds number. This suggests that the insight gained from the lower Reynolds number case under investigation may also be applicable to the experimental case.

Large-Eddy Simulation of the Tip Flow of A Rotor in Hover
R. Mittal, George Washington University

The blade-tip vortex is one of the most important aerodynamic features of a helicopter rotor wake. The strength, size, location and orientation of the tip vortices affect the blade loads and rotor performance. The overall goal of the current project is to develop a large-eddy simulation (LES) capability to simulate the rotor-tip vortex and use these simulations to perform a detailed analysis of the dynamics of this flow. In the last year tip-flow simulations have been carried out on a number of different grids. Based on a preliminary assessment a 460 x 179 x 150 grid is being used for the first production run. The outflow boundary is set to one chord in the wake of the airfoil. It is expected that this will produce tip vortex data at wake ages of 0.5, 1, and 3 degrees, which are stations where experimental data is available. 12 processors of a 2.8 GHz Pentium Linux PC have been used for these simulations. Simulations have been carried out at chord-based Reynolds number of 100,000 and Mach number 0.26 and rotational effects have not yet been included. Figures 2(a, b) show isosurface of enstrophy contours in different planes in the wake of the NACA 2415 respectively, which clearly show the development of a strong and compact tip-vortex.
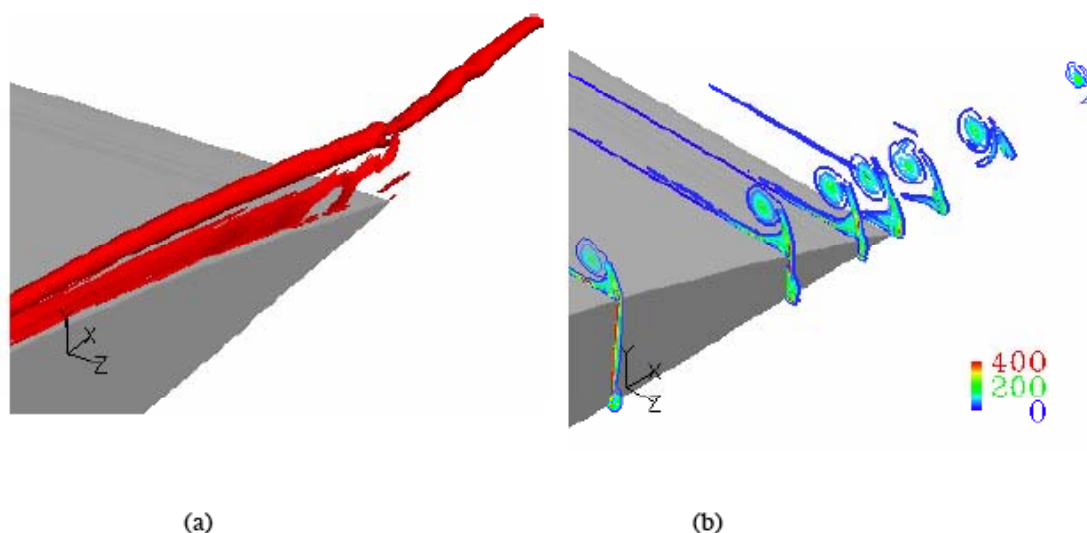
Figure 2. (a) Isosurfaces of enstrophy in tip-flow simulation Re=100,000, M=0.26. (b) instantaneous enstrophy contours in different planes from the tail.

Deformation and Failure Behavior of Heterogeneous Materials
K. Ravi-Chandar, The University of Texas at Austin

In most Army applications that use composite materials, the constituents are under multiaxial loading conditions. It has also been shown that confining compression can enhance their performance under impact loading. This project is studying the effect of confining compression on composite strength and damage progression. Professor Ravi-Chandar is also developing approaches to create confining compression through microstructure design (lay-up). To initially determine the local mechanical behavior of the matrix material, the confining cylinder experiment was used. Their experiments have shown that under confined compression, PEEK can sustain a much higher high shear stress level than unconfined PEEK. They have found that realistic levels of about 30 ksi confining compression can be obtained by suitably altering the microstructure of the composite.

To translate this idea to the design and fabrication of fiber composites it is essential to generate such compression during processing. Many natural composites in plants and animals form in a helicoidal structure; adopting this strategy to engineered composites, they have fabricated composite panels with a helicoidal architecture. The helicoidal composite was generated by laying 40 plies at 10 degree increments, resulting in two turns of the helix with four additional layers oriented along the zero direction at the middle. Symmetry about the midplane was maintained in order to eliminate coupling between extension and bending/twisting. The helicoidal structure provides a nearly continuous grading of the in-plane stiffness in the thickness direction and therefore reduces the interlaminar shear stresses. In addition, favorable thermal residual stresses

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are built into the plate during fabrication.

When compared to the cross-ply composite, the helicoidal composite exhibits significantly higher stiffness, strength and damage tolerance. Examination of the failure patterns of helicoidal specimen revealed the underlying reasons for its significant damage tolerance. A complex pattern of matrix cracks and fiber breaks is generated progressively. Matrix cracks can form transverse to the loading direction only in two of the layers – the 90° layers. In all other layers, matrix cracks form at different angles according to the fiber architecture, but are all less than 90°. Observations indicate the planes and directions of matrix cracking occur in the different layers. The distributed and progressive nature of failure results in a significant increase in the damage tolerance of the helicoidal composite architecture

Plate bending tests were performed on circular plates clamped at the boundaries and loaded by a spherical punch at the center. Comparisons of the response of a 40 layer helicoidal architecture with a biaxial 24 layer [+45/-45] composite and a uniaxial composite were made. The composite plates were nearly of the same total thickness, but all quantities are plotted with the appropriate thickness normalization. The nonlinearity observed in all of these tests is due to the large deflections of the plates. The unidirectional specimen, dominated by the matrix properties, exhibits the weakest response. At the peak point, the maximum load was 703 lbs corresponding to a load-point displacement of 0.187 in, and the laminate instantly broke to two parts. Due to the discrete nature of the +/- 45 composite, it also developed cracks in a catastrophic manner and delaminated across the entire plate diameter at a load of 2520 lbs corresponding to 0.274 inch of load-point displacement. On the other hand, the graded nature of the helicoids allowed for a reduction in the interlaminar shear stresses and hence delamination was delayed until much larger plate deflections and a corresponding increase in the load carrying capacity.

In spite of the graded nature of the helicoidal composites, once the delamination was initiated, it grew catastrophically resulting in a significant load drop. This is because delamination is controlled by the interlayer matrix and this is not affected significantly by the graded architecture; therefore improvements in the fracture energies cannot be obtained by altering the in-plane architecture alone. This has commonly been approached through a three dimensional fiber architecture obtained either by woven fabric reinforcement or through cross stitching or stapling. In this project, the stapling approach was adopted as a first step. The helicoidal composite stapled through in an axisymmetric pattern with the Z-reinforcement provided by steel staples of cross sectional area 0.00125 in^2 with approximately 11 staples per in^2; as a result, roughly 1.35% of the area is covered by the staples. The staples are introduced into the composite before curing; during insertion, the easy mobility of the fibers results in very little damage to the fibers; they simply move aside to allow the staple to penetrate. The influence of the staples on the composite toughness has been examined in a double cantilever beam (DCB) test; the fracture toughness of the stitched specimen normalized by the fracture toughness of the unstitched specimen was examined. The stitched

composite exhibits a stick-slip crack growth associated with severing of each staple. The fracture toughness of the matrix governs this cracking mode in the unstitched specimen and was found to be 1.18 psi in$^{1/2}$, while for the stitched composite, the effective toughness is at least 2 times larger. Clearly, by cross stitching at a higher density the toughness may be increased even more significantly.

Low speed impact tests were performed on the stapled helicoidal and the ±45° composites to understand damage evolution under impact. The striker used was a polycarbonate (PC) rod, two inches in diameter and four inches long with a blunted conical tip made of solid steel attached to the front end. This striker was loaded into the barrel of an air-gun and launched by air pressure. In this air-gun, the striker was propelled using an air pressure of 80 psi; the speed of the striker before hitting with the laminate was measured to be 55 m/s corresponding to impacting energy 732 J. To isolate damage occurring at the impact site from long term damage from stress accumulation at support points, the specimen was simply hung by a string in front of a catcher tank. The tank was filled with foam and clay to decelerate the specimen softly for recovery and observation of the impact induced damage. The normal to the specimen surface was aligned to be along the axis of the gun barrel to ensure normal impact on the plate. After impact of the ±45° specimen half the length of striker had penetrated through every layer of the laminate and the striker was embedded in the composite. The impacting force created cross cracks along the ±45° fiber direction and totally delaminated every layer; a pedaling failure can be seen in the image. The helicoidal specimen was impacted under the same condition; the post-test view of the laminate shows that the damage in this specimen was localized to the region of the impact. On the front side – the impact side – there was a small circular indentation caused by the striker tip and on the back side there were matrix cracks parallel to the fiber direction and delamination of the first layer was observed. The specimen was then sectioned and the delamination of the interior layers was verified. In spite of this, viewed in contrast to the observations on the ±45° specimen, we concluded that this helicoidal specimen was far below the penetration threshold.

It has been demonstrated through the plate bending test and the projectile impact test that the helicoidal composite exhibits superior properties. This difference is even greater when reinforced in the z-direction by a small amount of reinforcing staples. The helicoidal composite design has been shown to provide superior performance in terms of energy absorption and areal weight density. Specifically it is expected that this development will provide significant reductions in the areal weight density of composite structures for body armor and vehicle protection systems; judging from the trials on the carbon epoxy, this could be about 30 to 50% compared to conventional architecture.

±45° Specimen after impact   Stapled helicoidal specimen after impact

Figure 3. Plate bending tests

Interfacial Control of Microstructurally Induced Dynamic Failure Modes in Cubic Polycrystalline Materials
M. A. Zikry, North Carolina State University

The long-term objective of this work is the development of new predictive capabilities to understand how crystalline structure, grain-boundaries and other microstructural effects, link to failure at the macroscopic level. Three-dimensional computational techniques have been developed that account for the evolution of dislocation populations that are consistent with carefully controlled in situ TEM and SEM measurements and observations in f.c.c. and b.c.c. crystalline structures subjected to extreme changes in temperature, pressure, strain-rate, and strain. Efforts are currently underway to incorporate these approaches in large-scale codes that can be accessed by DoD and DoE laboratories. Dislocation-densities are treated as internal variables on each slip-system and the evolution of these densities are coupled to GB effects and aggregate porosities. Based on this, new criteria have been developed to identify and potentially control dominant transgranular and intergranular failure modes. This computational approach is one that accounts for the simultaneous nucleation and evolution of failure surfaces at different spatial and temporal locations. Most computational analyses do not account for interfacial effects, such as GBs, subgrains, and cell walls, even though it is well understood that these interfaces can play a dominant role in deformation and fracture at different scales.

The reliability and life-service of crystalline metal and alloy systems subjected to extreme loading conditions have been severely hampered by the lack of understanding and validated predictive capabilities of how multiple failure modes, such as stress induced void initiation and coalescence. Intergranular and transgranular failure modes

can simultaneously initiate, interact, and evolve, and hence the control of these failure mechanisms is of essential importance in the design and reliability of different systems. How pile-ups form, and whether stress fields accumulate or are relaxed by GB distributions and orientations, GB morphology, and local cohesive strengths, can be determined and related to void nucleation, growth, and coalescence. These conditions can then be used with the proposed experiments to determine failure scenarios related to material rupture. Based on these predictions, optimal GB orientations and distributions can be predicted to avoid and potentially control energy dissipation and failure in systems subjected to extreme changes in temperature, strain-rates, and pressures.

Nanoscale Characterization of Failure Processes in Polymer Nanocomposites
Raman P. Singh, State University of New York at Stony Brook

The objective of this research is to develop and characterize polymer nanocomposites with optimally enhanced toughness, damage tolerance and mechanical properties. The primary specific tasks targeted to meet these objectives are: (a) investigate the fundamental nano/microscale failure processes in nanoparticulate-thermosetting polymer composites and establish relationships between reinforcement structure and toughening mechanisms; (b) establish novel testing and analysis procedures for sub-microscale fracture testing and quantification of energy dissipation mechanisms; and (c) develop thermoplastic polymer nanocomposites for lightweight and possibly transparent armor applications. Fracture processes and toughening mechanisms in thermosetting polymer nanocomposites are inherently governed by material heterogeneities that exist at nanometer length scales. The extremely localized effects of nanoscale heterogeneities on the fracture process are smeared out during conventional macroscale testing, and thus necessitate the use of nano/microscale characterization. This research investigation employs controlled nanoindentation and sub-microscale fracture testing procedures to characterize the nano/microscale fracture of polymer nanocomposites. In addition, employing high-resolution acoustic sensing of fracture events will facilitate quantification of energy dissipation mechanisms during crack initiation and growth. Finally, this investigation is developing nanoparticulate reinforced PMMA for transparent armor applications.

The research focuses on the application of depth sensing nanoindentation (DSI). In contrast to conventional techniques, this approach allows for direct nano-scale characterization of material properties with sub-micron spatial resolution. For example, it is possible to determine the fracture toughness and modulus within agglomerated and uniform dispersion areas of nanocomposites. DSI measures the indentation loads and displacements at very high resolutions during one complete loading-unloading cycle. Various currently available models use the unloading part of the load-unload history to evaluate the elastic modulus and hardness of the sample. All these models assume that the material undergoes purely elastic recovery during unloading, and hence, the slope at the beginning of the unloading curve is used to find the modulus. However, for materials like polymers, the creep effect is significant, which can be observed as the change in

displacement with respect to time while holding the load constant. The viscoelastic creep effect dramatically influences the subsequent unloading behavior and hence the slope of the unloading curve, leading to negative values, especially when the loading rate is small. Under these circumstances, power-law fits will generally not be applicable for fitting the unloading response of polymers. Therefore, a different model to handle the viscoelastic behavior of the polymers is under development.

A cube corner indenter was used to induce fracture in a brittle glass, in order to evaluate the applicability of DSI to measure sub-microscale fracture properties. The occurrence of radial cracks in the substrate was correlated with a change in slope of the unloading curve from a typical load-displacement plot for glass indented with cube corner indenter. The change in slope is minor and thus this technique requires refinement in the ability to detect fracture initiation and propagation during indentation. Currently acoustic sensing is being implemented to augment the experimental procedure.

Gas-Phase Diesel Fuel Combustion Chemistry
Ronald Hanson, Stanford University

One of the primary goals of this program was to develop an extensive, high-quality database of ignition time measurements and species concentration time-histories useful for the validation of chemical kinetic models of hydrocarbon oxidation. These studies (1) provide reliable target data for the validation of chemical kinetics models of ignition; (2) develop ignition time correlations to summarize the wide range of data; (3) critically review the existing ignition time literature for these hydrocarbon fuels, and (4) identify, and if possible, measure key reactions needed to reduce the uncertainty in the predictions of these mechanisms.

One set of these kinetic targets, the OH concentration time-history data, are unique, and offer the combustion modeler the first quantitative glimpse into the kinetics of the small radical pool (H, O, OH) that plays a critical role in the ignition process. Time-resolved measurements of OH radicals, for example, have provided the first direct experimental evidence of the theoretically-predicted radical suppression found in branched-alkane oxidation, but not in n-alkane oxidation, and have helped identify deficiencies in the initial decomposition pathways and rates in some models of 1,3-butadiene oxidation. More generally, these OH measurements provide quantitative measurements of the radical concentration levels and temporal behavior that occur during the multiple phases of oxidation, i.e., the initial fuel decomposition, the initial OH plateau or suppression period, the "ignition" phase, the peak levels of OH, and the final approach of OH to equilibrium. With these data, modelers will be able to refine their mechanisms based on actual radical chemistry measurements rather than using only macroscopic engineering parameters, such as ignition times and concentrations of stable combustion products.

Flame Spreading in Confined Propellants
K. K. Kuo, Pennsylvania State University

The gap distance between adjacent propellant grains in a propellant charge can have a strong influence on the flame spreading phenomena as well as propellant regression rate. Due to close proximity of neighboring propellant grains, the burn rate of the propellant grains can be different from their normal burn rate when the loading density is very high. If the propellant burn rate is enhanced by the close proximity of the adjacent grains or disks during the initial phase of the ballistic cycle, the requirement for achieving high ratios (e.g. 3.0) of fast-to-slow burn rate of layered propellants is even harder to achieve.

To partially simulate close gap burning conditions experienced in the ballistics of gun systems, a double-ended windowed strand burner (DEWSB) was utilized. The DEWSB allows the propellants to be fed toward each other to keep a constant gap as they burn. This device was designed to operate under a controlled manner so that data can be collected for a constant specified gap width for a period of time (on the order of 10 seconds). The DEWSB consists of a high-pressure vessel for housing two identical drive systems adjoined to a center windowed combustion chamber, a purge feed system, a surge tank to keep the chamber pressure at a constant level, and an exhaust system for the burned products and purge gas.

Comparing regression rate data of JA2 propellant burned in the double-end configuration to that of a single strand, an increase in the regression rate of about 30% was observed for the pressure range tested. This increase occurs for a certain gap width range, which was found to be a function of pressure. The enhancement of the burn rate is caused by the geometric confinement of the flame, which applies a greater energy feedback to the burning propellant surface.

Studies of the Burn Rate of Nanocomposite Thermites
Michelle Pantoya, Texas Tech University

Burn rates of thermites are typically calculated in terms of an average particle size that characterizes the bulk mixture. As particle diameter approaches the nano-scale the burn rate calculation becomes increasingly sensitive to changes in particle diameter. In this study, burn rate estimates for nano-scale particle composite thermites are statistically evaluated in terms of an integral that employs a probability density function (pdf) for particle size distribution and a diameter dependent burn rate equation. It is shown that the burn rates depend sensitively on the mean particle diameter and the particle size distribution. Both single mode and bimodal particle size distributions were studied. The analysis shows that as particle size is reduced to the nano-scale, the size distribution rather than solely the average particle size, becomes increasingly important. Large variability in burn rate is associated with large standard deviations in particle size. Combining nano-scale with bulk-scale particles in a bimodal distribution does not significantly increase the burn rate as compared to a composite consisting of strictly nano-particles. The results suggest that better reproducibility of the burn rate may be achieved experimentally by selecting a material with a narrow particle size distribution.

Mean burn rates have been examined based on diffusion controlled flame propagation in

nanocomposite thermites. Burn rates were evaluated using probability density functions for single mode and bimodal particle size distributions. It was shown that burn rates depend sensitively on the average particle diameter, and thus the size distribution strongly influences the burn rate and standard deviation (variations) in burn rate. The probability density function analysis shows that narrow size distributions result in higher burn rates and lower variations in burn rate. When employing a single mode size distribution, significantly higher burn rates are obtained for narrow rather than broad size distributions (i.e., 28 compared to 16 m/s). This behavior is more pronounced as the average particle size is reduced below 100 nm. For average particle diameters greater than 100 nm, there is little change in mean burn rate with broadening in the size distribution. For bimodal size distributions the same general trend is observed as in the single mode distributions. Overall, the reproducibility and reliability of the burn rate performance associated with nano-scale particles is strongly dependant on the size distribution of the particles. It is ideal to work with narrow size distributions because they ultimately result in lower standard deviations in burn rate and higher burn rates.

Many studies that employ nano-particles for enhanced combustion performance require the incorporation of convective or radiative mechanisms in determining burn rates. The influence of size distribution could be incorporated into these different models for burn rate and the influence of size distributions in reactions controlled by other mechanisms would be realized. This type of analysis could have an impact on the safe handling and use of nano-particle energetic materials.

Integrated Diagnostics and Reliability Forecasting for Hybrid Structures
Douglas Adams, Purdue University

Significant portions of Future Combat Systems are to be made almost entirely of heterogeneous materials because these materials are designed to be lightweight, strong, and durable so they can be rapidly deployed to contain growing threats around the world. The theoretical and experimental research undertaken in this project is developing techniques for assessing damage in these structures in real time to help ensure the effectiveness of the Army's weapon systems and to secure the personnel who operate these systems. The non-linear dynamics and structural mechanics techniques being developed here are being transferred directly to the Army Research Laboratory, Air Force Research Laboratory, and various defense industry contractors for use in diagnosing damage and forecasting structural reliability in heterogeneous structures. The unique aspects of this work are that it aims to provide a means for detecting, locating and quantifying damage in multi-component, multi-layer structures using sparse, unobtrusive transducer sets; recognizes that qualitative non-linear dynamical transitions in structural health are the key features to observe when determining remaining useful life; and distinguishes between structural damage and variability in the operating and environmental conditions in order to predict remaining life and avoid false positive/negative alarms. Many of the diagnostic systems that have recently been developed for heterogeneous structural systems are not capable of characterizing both

local and global types of damage and do not function properly when one or more transducers fail or when data contain operational noise. By recognizing that subtle transitions in structural health are exhibited by nearly all material and structural systems, the non-linear damage prognosis methodology in this research could transform the way the structural health monitoring and non-destructive evaluation communities approach life prediction in general. In the structural health monitoring community, there is a very high positive and negative false alarm rate in the majority of diagnostic techniques that have been developed because the effects of environmental variability are not taken into account in the majority of data interrogation algorithms. This work focuses on physics based and data driven methodologies to avoid false alarms using dynamic similarity models because unless the false alarm rate can be eliminated, the defense-industry will not widely implement diagnostic and prognostic measures in military assets.

To verify that wave beamforming can be used to process propagating elastic waves for the purpose of damage interrogation, steel and composites plates were used to perform experiments. Theoretical models for propagating waves in the plate were developed. In both the steel and the composite plates, the first step in applying wave propagation techniques for interrogation is to identify the dispersion curves so that they can be used in the beamforming algorithms. These curves indicate the change in wave phase and group velocity with frequency and direction of propagation. The measured slowness surface and dispersion curve for both plates showed excellent agreement with the theory of wave propagation for asymmetric Lamb mode waveforms. Various tests were performed on both plates including: (1) added surface masses to the composite plate, (2) active interference source in steel plate to simulate damage, and (3) a surface score on the steel plate. Experiments involving added surface masses to simulate local changes in stiffness with a 4 kHz interrogating waveform on the composite plate were conducted. A line of actuators was used to generate a plane wave, and three sensors were used to acquire waveforms and locate the masses. The results indicate that the locations of the masses with respect to the array at 74°, 48°, and 29° were properly identified using a pilot mode signal adaptive beamformer. Adams observed that the adaptive beamformer results were clearer than the conventional beamsteering results due to enhanced signal-to-noise ratios that are achieved using the proposed method. In a second set of experiments on the steel plate, an interfering signal from a second patch actuator was used to simulate lower amplitude interference wave scatter from damage at 20 kHz. Damage was successfully detected by subtracting the time series signal of the baseline and simulated damage cases at each of the six sensor locations and then beamforming was performed. The simulated damage source was accurately detected within 5% of the true position in this set of experiments. In a third set of experiments, a surface scratch on the steel plate was used to simulate damage using a six element sensor array. The actual and estimated scratch locations were found to match within one wavelength of the interrogating signal at 20 kHz. When damage interrogation results for traditional and optimal beamforming were compared in noise-free datasets, the results are nearly identical in noise-free laboratory environments; however, when strong directional noise sources are added in future experiments to mimic operational noise (e.g., gear box on rotorcraft, gas turbine engine), optimal beamforming is expected to perform far better than the traditional beamsteering

technique.

Evaluation of a critical crack tip opening angle fracture criterion
Kevin Lease, Kansas State University

The reliability and durability requirements for legacy and future Army vehicles will demand continuing improvements in designing and monitoring structural integrity. One aspect of this task involves the analysis of stable crack growth in advanced metallic materials. The critical crack tip opening angle fracture criterion represents a very promising approach for modeling stable crack growth and instability during the fracture process. The objective of this research is to extend the state of knowledge of the critical crack tip opening angle concept to envelope materials and applications of particular interest to the ARL's Vehicle Technology Directorate. This investigation included: (1) the development of a unique state-of-the-art crack tip imaging and data acquisition system to be used in the performance of the stable tearing fracture tests; (2) perform ance of stable tearing fracture tests on representative thicknesses of the Ti-6Al-4V titanium alloy used in flight critical components of the Army's AH-64 Apache and UH-60 Blackhawk helicopters; and (3) performance of two- and three dimensional elastic-plastic, finite element-based fracture simulations of these stable tearing fracture tests to evaluate the ability of the crack tip opening angle parameter to simulate the laboratory specimen behavior. This research project has yielded two very significant results:

a. The design, development, and refinement of a state of the art test control/monitoring system for performing stable tearing fracture tests.

b. The comprehensive characterization and evaluation (experimental and computational) of the stable tearing behavior and crack tip opening angle parameter for the Ti-6Al-4V alloy of particular interest to the ARL Vehicle Technology Directorate.

This system represents a very notable improvement in the state of the art of stable tearing fracture testing. Significant improvements include the capability of running these tests in a "continuous" rather than "incremental" manner and the capturing of true digital images rather than recording the stable tearing process on videocassette tapes, that later had to be transferred to the computer via a frame-grabber board, compromising quality. The apparatus developed for this study captured digital images of the crack tip incrementally at a rate of one image per second throughout the test, while simultaneously sampling the analog inputs (load, crosshead displacement, crack extension and load-line displacement LVDT signals) from the testing machine and peripheral sensors. All data and image acquisition functions are completed and controlled through a LabView virtual instrument based program operated from a personal computer. Crack length measurements were taken by using an X-Y translation stage equipped with a LVDT to precisely track the movement of the crack tip. Images were captured from a ½-inch chip charge coupled device analog signal digital camera by using a commercially available frame grabber board controlled by a LabView virtual instrument based program. The resulting images captured had an image size of 640 X 480 pixels with a calibrated resolution of

approximately 266 pixels/mm. The stable tearing behavior of Ti-6Al-4V alloy has been fully characterized for four thicknesses of sheet/plate, ranging from 1.34 to 16.0 mm. This evaluation has shown that only the thinnest of the specimens evaluated (1.34 mm) exhibited well-behaved stable tearing behavior. The three larger thicknesses exhibited very little (if any) stable tearing, with crack extension advancing rather quickly and often in non-self-consistent manner. Due to this behavior, experimental crack tip opening angle measurements were obtained only for the 1.34 mm thick sheet. However, using three-dimensional elastic-plastic finite element fracture analyses, computationally determined critical crack tip opening angles were determined for all four thicknesses. This result is quite significant in that it allows for stable tearing analyses to be performed, with confidence, on large air or ground vehicle components containing single or multi-site damage.

V. TECHNOLOGY TRANSFER

The transfer of basic knowledge, new information, novel techniques, computer codes, experimental procedures, etc., from the fundamental research program in the mechanical sciences to application takes many forms, from personal exchanges of information to actual assistance in hardware development, and can and usually does span many years. Consequently, the documentation of actual cases of technology transfer frequently proves to be elusive and is often difficult to define in concrete terms. Despite this, the Mechanical Sciences Program contains many excellent examples of the use of fundamental research results obtained under ARO support in Army and other Government laboratories, industrial development activities, and other fundamental research investigations. Several examples are described below.

Formal project summary documents, presentations and interim reports have been prepared and delivered to Mr. Elias Rigas at the Army Research Laboratory, Mr. Bob Evans at the Aviation and Missile Command and Dr. David Lamb at the Tank and Automotive Command in January 2003 and 2004. New interactions with Mr. Paul Decker at TACOM in road vehicle diagnostics & prognostics have also been initiated in spring 2004 with a summary presentation of the ARO sponsored research results. All significant developments including papers accepted for publication in this research have been reported to these collaborators for feedback and discussion. The preliminary results from this work have been well received by Army researchers, who now plan to apply the results to Army systems. Close and sustained interactions with Mr. Elias Rigas and Mr. Shawn Walsh in the Composites and Lightweight Structures Group of the Army Research Laboratory at Aberdeen Proving Grounds have resulted in several collaborative conference papers and three archival Journal papers in review. Mr. Rigas also visited the Ray Herrick Laboratories at Purdue University in October 2002 for a half-day meeting to review the research results and to tour the research facility. The PI visited the Aberdeen Proving Ground in January 2002 for a half-day meeting with Mr. Rigas and Mr. Walsh to review the research progress and discuss evolving ARL needs in the area of damage prognosis. Additional visits by these ARL partners to Purdue are being planned for

summer 2004. Continuous interactions with Mr. Bob Evans and Mr. Robert Esslinger from the Aviation and Missile Command (AMCOM) at Redstone Arsenal have resulted in research results presented at the 2002 International Mechanical Engineering Congress and Exposition in New Orleans, LO on the use of pseudo-repeated modes of vibration in axisymmetric parts such as the filament wound rocket motor casings for quantifying non-uniformity before usage. The PI also visited AMCOM to discuss the ARO research in spring 2002. Additional visits by these AMCOM partners to Purdue are being planned for summer 2004.

Professor Raj Singh, Ohio State University, has conducted research on the influence of sliding friction in rotorcraft geared systems. To assure Army relevance of his investigation, he conferred with engineers ARL/VTD located at the NASA Glenn Research Center and Sikorsky Aircraft Corporation, where they prepared a collaborative project. In particular, the 2004-05 RITA/NRTC project (in collaboration with ARL/VTD NASA Glenn and Sikorsky) will focus on experimental and application issues. This will ensure an effective transfer of the analytical methods that are being generated under the ARO project. The ARL staff (at VTD NASA Glenn) and approximately 25-30 companies (including the rotorcraft companies) active in gear analysis and design attended a review meeting of the members of a Gear Dynamics Consortium held at the Ohio State University, where he presented the results of his recent research. The computer simulation tools (based on his lumped parameter system models and analytical solution techniques) will be made available for transfer to ARL/VTD at NASA Glenn and Army helicopter contractors, after completing the models for the helical gears.

Professor John Steinhoff of the University of Tennessee Space Institute has been developing a new computational method for the treatment of small vortical scales in high Reynolds number incompressible flows. This method, known as vorticity confinement, is similar to the emerging technique of implicit large eddy simulation, although the focus of vorticity confinement is on vorticity. Recently, the AMRDEC Aeroflightdynamics Directorate has implemented vorticiy confinement in their TURNS and OVERFLOW rotorblade codes and used these computational tools to predict the onset of dynamic stall. Dynamic stall results have been obtained with the VR12 and NACA 0015 airfoils and compare well with experimental data.

The results of the high pressure hydrocarbon ignition and combustion research performed by Professor Ronald Hanson at Stanford University have found immediate and long-term use by several groups and agencies. The ignition time measurements, in particular, are already being used extensively by the combustion community for validation and refinement of large fuel surrogate reaction mechanisms. Several groups have used the measurements of the alkane ignition times and OH concentration time-histories in the long-term development of primary reference fuel kinetic mechanisms (C. Westbrook and W. Pitz, Lawrence Livermore National Laboratory; F. Dryer, at Princeton University; H. Wang University of Delaware), and in the development of plasma-assisted combustion models (S. Williams, AFRL). The measurements of the branched-alkane ignition times and OH concentration time-histories have found immediate use in the current DOE EERE program for the development of HCCI (homogeneous charge compression

ignition) engines (D. Assanis, University Michigan). This program strongly interacts with the automobile, truck and engine industries, and includes regular meetings with GMC and Caterpillar Corp. Shock tube measurement techniques developed under this program have been used in laboratory to measure to ignition times in gasoline and gasoline-surrogate fuel mixtures needed by industry for characterization of gasoline-surrogate reaction mechanisms (T. Sloan, General Motors Research and Development). Measurements characterizing energetic ignition experiments (shock tube ignition time measurements at high fuel concentration levels that general lead to detonations) are being used in the development of computational detonation models (C. Morris, NASA Marshall Space Flight Center). The measurements of the n-alkane ignition times, in particular those for propane, have been used by modelers at NRL (K. Kailasanath) in predicting and improving the performance of pulse detonation engines. Mie scattering and gas phase fuel detection methods using TDL (tunable diode lasers) developed and tested in our shock-spray interaction facility for the measurement of size distribution and fuel loading have been applied to: fuel injector characterization (E. Gutmark, University of Cincinnati, ONR), and pulse detonation engine development (C. Brophy, Naval Post Graduate School, ONR).

VI. DIVISION STAFF

Dr. David M. Mann
Associate Director, Mechanical Sciences Division
Combustion and Propulsion Research Program.

Dr. Gary L. Anderson
Branch Chief
Structures and Dynamics Research Program.

Dr. Thomas L. Doligalski
Branch Chief
Fluid Dynamics Research Program.

Dr. Bruce LaMattina
Branch Chief
Solid Mechanics Research Program

Pamela Robinson
Administrative Support Assistant

I. PROGRAM OBJECTIVES

The objectives of the Physics Program are to develop and exploit the physics knowledge base to create revolutionary capabilities for the Army of the future, and also to provide innovative solutions to current Army needs. Physics research investments produce major impacts on technology and military capability in areas such as target acquisition, small platform technology, and battlefield management. Past examples include the research on fundamental limits and metrics for image analysis that is now being used for target acquisition. In addition, past physics research included novel semiconductor charge transport in heterostructures that formed the foundation of optoelectronics and led to the discoveries recognized in the 1998 Nobel Prize in Physics. The use of stimulated emission for the generation of coherent radiation (i.e. the invention of the laser) was recognized by the 1964 Nobel Prize in Physics to Charles H. Townes and involved significant basic research supported by ARO. Additional discoveries include the following: photoemission and photoconductivity research which impacted current night vision technologies, acousto-electric interaction in piezoelectric crystals used in high-precision clocks for signal processing, ferroelectric liquid crystals used for high-quality image displays, and the theory of phase diagrams which enabled the growth of HgCdTe infrared (IR) radiation imaging devices now used in Gen II night-vision sensors.

The future continues to promise dramatically improved Army capability as a result of physics research. In support of this goal, the interests of the ARO Physics Division are primarily focused on areas most likely to have mission impact, namely: Condensed Matter Physics; Optics, Photonics, and Image Science; Quantum Information Science; Theoretical Physics and Nonlinear Dynamics; and Atomic and Molecular Physics. This includes the Physics sub-disciplines of: (1) Solid State Physics; (2) Interface/Surface Physics; (3) Atomic, Molecular, and Optical Physics; (4) Materials Physics; (5) Cross-Disciplinary topics; and (6) Classical Phenomenology.

II. RESEARCH AREAS

A. General Information

The ARO Physics Division uses program themes called "workpackages" whose title and subject matter align with active areas of academic research but whose emphasis and motivation are derived from Army and DoD requirements and needs. These names have been somewhat dynamic in time, and the changes reflect recommendations from various physics strategy plans, especially those derived from the triennial Physics Coordinating Group (PCOG) meetings.

The basic research portfolio of the ARO Physics Division balances a needs-driven responsiveness to current Army requirements, on the one hand, and an opportunity-driven exploitation of emerging scientific findings for revolutionary Army capabilities, on the other hand. The Physics Division prides itself in a strong track record of nurturing, maturing, and transitioning opportunity-driven research to engineering practice for

eventual fielding. In addition, the Physics Division has worked with other agencies, especially DARPA, to develop physics-based solutions to nearer-term Army needs. The current distribution of Physics Division research investment continues to maintain a healthy balance of opportunity-driven and needs-driven research.

The Physics Division workpackages, along with their scientific definitions and military relevance, are described in the following.

B. Thrusts and Trends/Workpackages

CONDENSED MATTER PHYSICS PROGRAM

The condensed matter physics program investigates fundamental physical phenomena to demonstrate new or enhanced functionalities that can be exploited for use by the Army. There are four major thrusts within the condensed matter physics workpackage: nanometer-scale physics, electronic and photonic band engineering, soft condensed matter physics, and multifunctional probes and control.

Nanometer-scale physics – Experimental investigations of nanometer-sized materials and novel nanostructure composites provide insight into physical phenomena operative in confined geometries and elucidate how these phenomena may be exploited. Interests include collective and cooperative nanoscale phenomena and understanding the evolution of atomic to nanoscale to bulk behavior. Emphasis is on revealing novel phenomena having the potential to deliver revolutionary capabilities to Army-relevant applications such as novel optical and infrared materials and innovative electronic and optoelectronic devices.

Electronic and Photonic Band Engineering – Electronic band engineering is useful for the development of militarily relevant device functionalities such as infrared emitters based on quantum cascade lasers and lasing without inversion in multiple quantum well semiconductors. Photonic-band engineered materials have applications such as novel microcavity emitters, infrared sensors, enhanced microwave components, and low emissivity materials. The objective is to use electronic and photonic band engineering independently and together, as adjustable design degrees of freedom to develop devices and materials with unique functionality. Methods of solving the inverse problem, finding optimal materials parameters based on prescribed functionality, are of particular interest. Applications include infrared emitters and detectors and micro-photonics for smart sensors.

Soft Condensed Matter Physics – The ability to deliver optimum performance in soft materials such as organic semiconductors, composites and biological materials is rooted in an understanding of the physical phenomena that give rise to their structural, electronic and optical properties. The primary objective is to understand the underlying physical properties of soft materials at the quantum level. Of particular interest is a fundamental understanding of the interface between soft materials and inorganics, and between soft

materials and nanostructures. Target applications include flexible electronics, novel organic-based electronic and optical devices, and biocompatible devices.

Multifunctional Probes and Control –To characterize and control phenomena in semiconductor heterostructures and nanostructures, it is important to combine the high spatial resolution of nanoprobes with the ultra fast temporal or adjustable spectral resolution of optical probes. The objective is to observe and control the dynamical evolution of physical phenomena in these materials at all relevant length- and time-scales. Although the development of probes of nanometer-scale behavior is still sought, the exploitation of such tools to demonstrate feedback and control of phenomena is of increasing interest.

THEORETICAL PHYSICS AND NONLINEAR PHENOMENA

This program emphasizes fundamental theoretical physics that is well coupled to experiments and to both long and short range Army needs. It encompasses the Physics of many-body interactions, from the quantum mechanical to classical, and from atomistic scales to continuum, as appropriate. Both equilibrium and non-equilibrium states of physical systems are considered. Quantum and classical statistical physics are encompassed.

The program has been very fruitful in solving a number of disparate Army problems. Examples are the first principles calculation of the phase diagram of HgCdTe for night vision devices, using an extension of the Ising model, which helped implement epitaxial growth schemes for the quality HgCdTe material needed for Army night vision devices. Novel Army relevant ferroelectric materials were theoretically predicted through quantum mechanical calculations and afterwards experimentally grown and analyzed showing agreement with the theoretical predictions. In the continuum physics domain, new crystal symmetry principles were combined with Lagrangian mechanics and perturbation theory to determine the exact manner of "clamping" SAW devices to achieve higher levels of stability against vibrational disturbances. This was then experimentally achieved and this provided the necessary improved time keeping.

The physics of electron correlations in real material systems remains a point of concern. Existing methodologies, such as the celebrated Density Functional Theory methods, still cannot solve some outstanding problems in highly correlated electron systems. New theoretical tools are needed to explore important classes of Army-relevant materials. Close coupling between theory and experiments are being pursued in this program to solve these outstanding correlation problems. Mathematical physics techniques are also being explored for this goal.

Electron correlations have counterparts in photon correlations. Novel aspects of lasers and of partially coherent light open up new vistas in signal processing. This area, initiated by ARO decades ago, is now being carefully explored in this program to bring to fruition a number of applications, both military and commercial. Moreover, since material systems interact with externally applied electromagnetic radiation, be it in the

visible, IR, THz, GHz, or MW, such interactions are explored. Applications range from signal intelligence, to IFF, to target acquisition.

A fundamental aspect of the physics of many-bodies is the manner in which "elementary interactions," quasi particles, and collective phenomena arise from the interaction of subunits of atoms and molecules. A hierarchy of subsystems evolves, even up to a multi-quantum-well type structures. This program includes the exploration of ways of using these for improved signal processing applications. Thus phonons, magnons, plasmons, excitons, polaritons are explored. The coupling of electrons (as fermions) to photons and other bosons necessarily becomes part of the program. In turn, the time evolution of these many-body systems and quantum transport must be considered.

A major part of the program encompasses nonlinear interactions. Solitons, as special eigenstates of nonlinear systems, are explored both in the optical and MW regions, in various nonlinear media. The microscopic origins of the nonlinearities are emphasized to be able to produce new materials with specific and potentially enhanced properties. Quantum mechanical theories and computational methods surface as part of this program.

QUANTUM INFORMATION SCIENCE

Quantum mechanics provide the opportunity to perform highly nonclassical operations that can result in exponential speed-ups in computation or ultra-secure transmittal of information. This workpackage seeks to understand, control, and exploit such nonclassical phenomena for revolutionary advances in computation and in secure communication. There are three major areas of interest within this workpackage.

Fundamental Studies - Experimental investigations of the wave nature of matter, including coherence properties, decoherence mechanisms, decoherence mitigation, entanglement, nondestructive measurement, complex quantum state manipulation, and quantum feedback are of interest. The objective is to ascertain the limits of our ability to create, control, and utilize quantum information in multiple quantum entities in the presence of noise. Of particular interest is the demonstration of the ability to manipulate quantum coherent states on time scales much faster than the decoherence time, especially in systems where scalability to many quantum bits and quantum operations is promising. Theoretical analyses of nonclassical phenomena may also be of interest if the work is strongly coupled to a specific experimental investigation, as may proof-of-concept demonstrations in atomic, molecular, and optical systems as described in the Atomic and Molecular Physics Program.

Quantum Computation - Quantum computing will entail the assembly and manipulation of hundreds of quantum bits. The objective is to demonstrate tremendous speed up of computations. Experimental demonstrations of quantum logic performed on several quantum bits operating simultaneously would represent a significant advance toward that ultimate goal. Demonstrations of quantum feedback and error correction for multiple quantum bit systems are also of interest. In addition to the algorithm for factoring, there is particular interest in developing algorithms for solving an NP-complete

problem for use in resource optimization, and in developing quantum algorithms to simulate complex physical systems.

Quantum Communication - The ability to transmit information through quantum entanglement distributed between spatially separated quantum entities has opened the possibility for an ultra-secure means of communication. Beyond quantum cryptography, the objective is to demonstrate quantum communication of information based on distributed entanglements such as in quantum teleportation. Of particular interest would be the demonstration of long-range quantum entanglements, entanglement transfer among different quantum systems, and long-term quantum memory.

ATOMIC AND MOLECULAR PHYSICS

Research in atomic and molecular physics will create fundamentally new capabilities for the Army, as well as providing the scientific underpinnings to enhance existing technologies. Topics of interest include methods of isolating and cooling individual atoms, ions, and molecules, as well as dilute gasses of these; quantum degenerate atomic gasses, their excitations and properties, including mixed species, mixed state, and molecular; matter-wave optics and matter-wave lasers; nonlinear atomic and molecular processes; quantum control; novel forms and effects of coherence; and emerging areas. Applications range from ultra-sensitive detectors including improved inertial sensors and navigation aides; to sensor protection; to novel sources. In addition, areas of application include novel materials processing, e.g., by obtaining increasingly complex molecules, clusters, or patterned structures, as hybrid or composite materials, or through quantum control.

Matter-wave Optics - Matter waves offer new or enhanced capabilities in a number of areas. For example, cooling, trapping and coherent control of atoms and molecules may provide ultra-sensitive sensors, including gyroscopes for inertial navigation, or ultra-high resolution lithography. In addition to the sensitivity advantage of matter waves, they also have additional degrees of freedom such as mass and associated "external" quantum states (together with a richer internal state structure) that might provide handles for new sensing capabilities. The use of coherent matter waves and Bose condensates (e.g., as in a "matter-wave laser") requires basic research to better understand issues such a coherence and decoherence, trapping and out-coupling techniques, and "matter-wave optics" to collimate, diffract, split, combine, interfere and otherwise manipulate matter waves. Laser cooling and trapping of atoms and molecules also may provide proof of principle demonstrations of key components of quantum computing.

Molecular Physics - The molecular physics program is distinguished from programs in chemistry and in materials science. One distinguishing feature is its focus not on synthesis, but on the underlying *mechanisms*, such as electronic transport, magnetic response, coherence properties (or their use in molecule formation/selection), and/or linear and nonlinear optical properties. The systems of interest are well-defined molecules, generally small or of high symmetry, and their functionalized variants. We are seeking to broaden the scope of topics covered in the molecular physics part of the

program. Most of the recent explosive progress in atomic physics can now be mapped onto the molecular regime, though achieving the equivalent results is much more difficult. Moreover, much new understanding of molecular physics will come from the process. Cooling, trapping, and Bose condensing molecules fall into this scope. Recently seen coherent molecular superposition states, a novel form of matter, are another example. Applications of quantum control in the molecular domain are yet another.

Fundamental Atomic and Molecular Physics - The Division also has a general interest in exploring fundamental atomic and molecular physics topics that may have an impact on technologies of interest to the Army. For example electromagnetically induced transparency allows propagation of light through a medium that is normally strongly absorbing, and it also provides unique access to nonlinear effects that could lead to very efficient frequency multiplication and tunable sources of electromagnetic radiation. The understanding of the physical mechanisms behind long range, white light propagation of ultra-short, ultra-intense pulses is another example of a topic of interest with unresolved atomic and molecular physics issues. General issues of quantum coherence, quantum interference, and quantum control and their numerous potential applications are also of interest.

OPTICS, PHOTONICS AND IMAGING SCIENCE

Research in optical physics and imaging science will create fundamentally new capabilities for the Army, as well as providing the scientific underpinnings to enhance existing technologies. Topics of interest include unconventional optics for enhanced imaging and detection, and nonlinear atomic and molecular processes for sensor protection and optical processing. Areas in photonics include photonic bandgap engineering, photonic fibers, and tunable bandgap materials. Image science, automatic target recognition, and sensor fusion issues are also addressed in this program.

Optics - Optics is a wide field that encompasses all aspects of optical physics. Nonlinear processes and quantum optics are included. Coherence is another theme. When a laser beam passes through a scattering medium, depending on the amount of randomness and the scattering processes involved, the degree of coherence is altered. A number of physical effects have been observed and explained, but many issues need investigation. The degree of coherence can affect such things as imaging, information transfer, and target recognition. Multiple scattering and partial coherence are also dependent on both volume effects and scattering from many interfaces. In addition, the physics of new optical materials, such as negative-index materials is of interest. The Division seeks theoretical and experimental work on these topics.

Another area of research concerns high-energy femtosecond laser physics. High-energy ultrashort pulsed lasers have achieved intensities of 10^{21} W/cm^2. The applications of these pulses include high harmonic generation, nanolithography,

3-D internal design, micromachining, particle beam acceleration and control, and light filaments. In the near future even higher intensities are expected. Theoretical and experimental research is needed to describe and understand how matter behaves under these conditions, from single particle motion to the effects in materials, and how to generate these pulses and use them effectively.

Photonics - Interest continues in the development and use of photonic band engineered materials for applications including novel microcavity lasers and light emitting diodes (LEDs), and tunable bandgap materials for novel applications and sensors. The objective is to use electronic and photonic band engineering independently and together as adjustable design degrees of freedom to develop devices and materials with unique functionality. Methods of solving the inverse problem, finding optimal design rules based on prescribed performance objectives, are of particular interest. Applications include infrared emitters and detectors, low observables, and microphotonics for smart sensors, or new methods in imaging.

Imaging - The Division has an interest in extending the capabilities of optical components and systems. Examples of approaches include hybrid optical/digital systems to minimize classical optics aberrations and adaptive optics to overcome atmospheric distortions. Also of potential interest are new approaches to coherent or ballistic imaging through turbid and scattering media. Several other imaging enhancement technologies, such as hyperspectral imaging and infrared polarimetric imaging, have been receiving attention recently. The Division has an interest in the identification and resolution of basic research issues that would demonstrate the utility of these approaches. Also of interest are other approaches that would increase the resolution or contrast of scenes, or otherwise improve the information quality of images.

III. SPECIAL PROGRAMS

Most of the Physics program involves single-topic, single-investigator efforts. The exceptions are the multi-topic/multi-investigator efforts funded by the Multidisciplinary University Research Initiative (MURI) program. The Physics Division administers MURI grants in Quantum Computing including Photonic Quantum Information Systems, Non-classical Information Science, Quantum Communications, and Designer Photon Sources and Detectors, as well as MURIs in Biomimetic Materials with Adaptive IR Responses, Solitonic Computing, Ultracold Atom Optics, THz Technologies, Intelligent Displays, Nanoscale Imaging with Integrated Spectroscopies for Chemical and Biomolecular Identification, and Giga-Hertz Electromagnetic Wave Science and Devices for Battlefield Communications. Together with the Office of Naval Research, ARO Physics manages two additional MURIs in Optical Clocks. A new MURI on Quantum Imaging will begin in FY 2005. All of these efforts fall under the workpackages discussed above, but are highlighted here because they indicate areas in which the Division has placed increased resources.

The Division had two MURI programs start in 1999. One was in Non-classical Information Science. The other is in Biomimetic Materials for Adaptive IR Response.

The Non-classical Information Science MURI addresses the revolution facing computational science wrought by quantum mechanics and nanotechnology. This was awarded to the University of Rochester, Harvard, Cornell, and Stanford Universities. The steady shrinkage of logic devices seen over the last 30 years will halt in the next twenty years, as transistors approach the size of individual atoms. Before that happens, increasingly dominant quantum mechanical effects will limit transistor performance. In order that quantum mechanics presents an opportunity rather than a barrier to further technological advance, new computation and communication paradigms must be discovered and limits ascertained. This MURI was to attempt to do just that, combining expertise in theoretical physics, atomic, molecular, optical, condensed matter experimental physics, and classical information theory.

The second MURI awarded in 1999 was on Biomimetic Materials for Adaptive IR Response, a topic motivated by the need for adaptive materials for a number of applications such as environmental control, biological agent detection, and possible technology transfer to Army Labs working on stealth applications. Two centers were formed: one at Rice University working on nanoshell materials and one at UCLA working on layered polymer composites. Additional universities that participate are Oklahoma State University and the University of Houston in the Rice Center and the University of Florida in the UCLA Center. Another partner in the UCLA Center is Allied Signal Corporation, which receives no funds but collaborates for the purpose of technology transfer in the environmental control applications area.

The Division had five new MURI programs that started in 2000: two in Quantum Communication, two in Ultracold Atom Optics, and one in Solitonic Computing.

The Quantum Communication MURIs are consortia lead by the California Institute of Technology and the Massachusetts Institute of Technology. The objective of these MURIs is to develop the hardware and error correction protocols needed to construct a quantum communications network. It is anticipated that quantum communications techniques will provide ultra-secure communications, based on teleportation of quantum states that are impossible to eavesdrop.

The Ultracold Atom Optics MURIs are a pair of complementary MURIs, each a consortium to itself. One is led by the University of Colorado; the other by Stanford University. Four Nobel Laureates are part of these consortia, with two receiving their Prize in 2001 while under ARO support. The objective of these MURIs is to utilize the recent advances in laser trapping and cooling of atoms, and the formation of Bose condensates, in order to create and use coherent matter waves to make new classes of ultra-sensitive detectors and sensors. Various configurations of atom interferometers are used to sense acceleration, gravity and gravity gradients, and rotation. Even seemingly mundane issues such as gratings are of interest, as there are numerous ways to implement them, including microfabricated structures on the one hand and optical approaches on the

other. Integrated wave-guide atom interferometers are being developed—essentially "interferometers on a chip." The ability to guide a single mode has recently been demonstrated. A new DARPA program on precision navigation, PINS, began this year, building on the results from these MURIs.

The Solitonic Computing MURI, which also began in 2000, is lead by the University of Central Florida. The goal of the program is to develop reconfigurable spatial solitons that can be used in "gateless" computation. The research could result in unique, super-parallel computation modalities that will greatly enhance capabilities in signal processing, optical computing, filtering, and target designation and tracking. Further goals of the MURI are to demonstrate superparallel optical computing that will interface smoothly into traditional optical components and systems, and to demonstrate a seamlessly integrable optically controlled network routing system whose throughput will exceed existing modalities by orders of magnitude.

In 2001, a new MURI was begun focusing on Intelligent Displays. This was awarded to Georgia Tech, the University Pennsylvania, Penn State University, and Oregon State University. The goal is to demonstrate how pixels in display screens can be made interactive with each other, to process information "intelligently." The MURI team hopes to show the rudimentary steps needed for this to happen, leading to novel proof-of-concept demonstrations of information display, communication, and edge detection. The MURI also hopes to demonstrate insertion of some rudimentary cortical brain functioning dynamics into displays and show how to extract "emergent behavior" — a signature of "intelligence."

The year 2003 saw the start of a new MURI on Photonic Quantum Information Systems to Stanford University. The goal here is to develop on-demand sources of single and entangled photons, using InGaAs quantum wells, and with parametric down conversion, respectively. Detectors of single photons and photon pairs will be fabricated in impurity-doped silicon, superconducting tungsten or niobium thin films, and periodically poled lithium niobate. Quantum memory registers will be developed in a cavity and in InGaAs quantum wells and quantum dots. Devices it is expected will ultimately operate at a variety of wavelengths and temperatures.

In FY 2004 two new MURIs were begun. One is focused on Nanoscale Imaging with Integrated Spectroscopies for Chemical and Biomolecular Identification. The other is on Giga-Hertz Electromagnetic Wave Science and Devices for Battlefield Communications.

The Nanoscale Imaging MURI focuses on developing a plasmon-based toolset for biotechnology. This was awarded to Rice University and the University of Texas at Austin. There will also be collaboration with Lawrence Livermore National Laboratory. Envisioned are (i) highly optimized surface enhanced Raman spectroscopy substrates, and (ii) scanning probes functionalized for plasmon resonance to combine plasmon-based spectroscopies with scanning probe technology. The goal of the MURI is to provide the life scientist with tools to enable the study of proteins and protein-containing structures such as viruses in their native environments, without crystallization and in real time.

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The second 2004 MURI focuses on GHz Electromagnetic Wave Science and Devices for Advanced Battlefield Communication was awarded to a team of universities: the University of Colorado at Colorado Springs, Colorado State University, the University of California at Berkeley, Duke University, the University of California at Irvine, and Oakland University. The driving force behind this research is the advent of new growth techniques and novel materials that are providing more flexibility to exploit the physical processes allowing GHz signal manipulation. The relevance of the GHz frequency range to the Army mission includes secure, high bandwidth wireless communication, RADAR detection, and target identifying RADAR.

For FY 2005 one new topic was approved, and competition is currently in progress. The topic is Quantum Imaging, and includes new methods of sub-diffraction limited imaging using quantum entanglement, and the possibility of "ghost imaging" where once can reconstruct an image without the photons that actually interacted with the object.

IV. SCIENTIFIC ACCOMPLISHMENTS

Observation of Superfluidity in an Optically Trapped Fermi Gas
John E. Thomas, Duke University

Interacting atomic Fermi gases can serve as model systems for fundamental interactions in nature. In contrast to the systems they model, atomic gases can be readily varied in density, temperature, and interaction strength. The interaction strength in certain atomic gases, such as ^{6}Li, is magnetically tunable by means of Feshbach resonances. In the region of a resonance, the interactions can be tuned from strongly attractive to strongly repulsive. Fermi gases containing two or more spin components permit studies of interesting physics in many different domains. For example, they allow an investigation of the scaling behavior of new theories of few-body interactions for strongly interacting particles in nuclear matter. Two-component Fermi gases can also serve as atomic gas analogs of models of superfluidity and of high temperature superconductivity. Moreover, in the vicinity of the Feshbach resonance, nonlinear matter-wave scattering becomes important, which has applications in both "traditional" non-linear optics and in the new field of atom optics. Hence, this work is crosscutting. These are also tabletop experiments, something not ordinarily possible in studies of say nuclear matter, or high-energy physics (effective theories of the strong interactions), or astrophysics (compact stellar objects). Yet this work applies to them all.

Work during this past year has included the observation of what is likely a superfluid Fermi gas. Measurements were made of the frequencies and damping times for the radial hydrodynamic breathing mode of a trapped, highly degenerate gas of ^{6}Li atoms near the Feshbach resonance at a magnetic field of 822 G. A cross check of the measurement method was provided by observing the breathing mode of a noninteracting gas. One method for distinguishing between a BEC and a superfluid Fermi gas is to examine their collective hydrodynamic modes at low temperature where the trapped gas is collisionless. By doing so, this group has now observed collective oscillations at a magnetic field just

above the Feshbach resonance, a place where the two-body physics does not support a bound state. A breathing mode was observed at precisely the hydrodynamic frequency. In addition, highly anisotropic hydrodynamic expansion was measured, consistent with their previous experiments. The damping time increases rapidly as the temperature is lowered, consistent with a transition from collisional to superfluid hydrodynamics at a temperature between 0.3 and 0.2 T_F. The data are not consistent with either collisionless mean field evolution or collisional hydrodynamics. However, it is consistent with a superfluid behavior. Depending on the pairing mechanism, this may be an analog of BCS-type or of high-temperature superconductivity. In fact, as a "clean" system, it can be a model (e.g. with tunable, or more generally, substitutable, interactions) for different kinds of superconductivity.
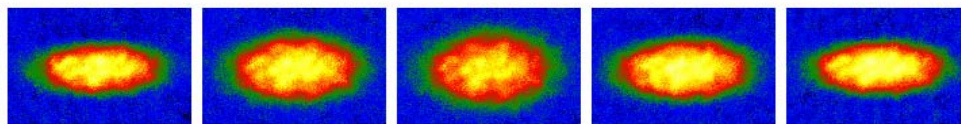
Figure 1. Images of an oscillating cloud of a strongly interacting Fermi gas. The dynamics is strong evidence for superfluidity in a regime where BEC is not allowed.

Research Studies on Electromagnetically Induced Transparency
Stephen Harris, Stanford University

The central theme of this work is the study and exploitation of quantum coherences and specifically one implementation of it, namely electromagnetically induced transparency (EIT), for creating new types of nonlinear interactions, processes, and optical devices. Many new types of effects, for example, slow light and spatially compressed light, become possible.

This past year has seen the attainment of a milestone result: The generation of an optical pulse where the spectrum is sufficiently broad that the waveform is a single cycle in length, and where the temporal shape of this waveform may be synthesized. Specifically, they have generated a train of single-cycle optical pulses with a pulse width of 1.6 fs, a pulse separation of 11 fs, and a peak power of 1 MW.

To synthesize a periodic waveform that is not sinusoidal, it is required that the radiation be phase coherent across its spectrum, and that the bandwidth of the radiation be large

compared to its central frequency. Control of the temporal waveform is obtained by dispersing its spectral components, adjusting their phases, and recombining the components onto a target medium. To obtain a multi-octave phase-coherent spectrum, they drive the fundamental vibrational transition in deuterium slightly off resonance. This produces a set of equidistant, mutually coherent sidebands that are separated from each other by the difference of the frequencies of the driving lasers and extend from 2.94 microns in the infrared to 195 nm in the ultraviolet. A subset of seven sidebands extending from 1.56 mm to 410 nm is dispersed and sent through a liquid crystal spatial light modulator where the phases of these sidebands are independently adjusted to Fourier synthesize the desired waveform in a target xenon cell (figure 2). The phases are adjusted to compensate for the dispersion of the intervening glass windows and optics and also for the phase change that results from the phase shift of the spectral components as they propagate.
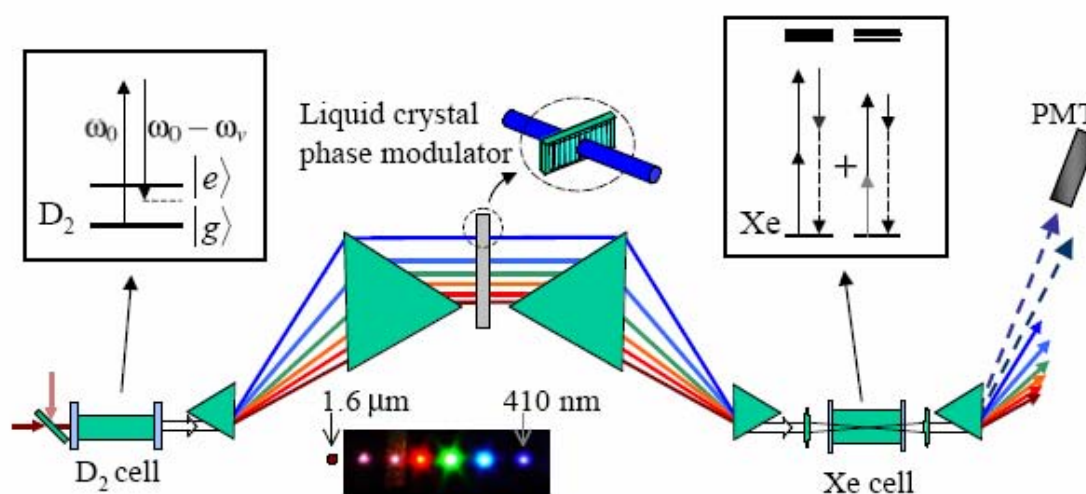
Figure 2. Experimental set-up for temporal synthesis and characterization. Seven Raman sidebands are dispersed and their phases are independently varied via a liquid crystal modulator. The sidebands are recombined and focused into a target Xe cell. A solar-blind photomultiplier measures ultraviolet radiation that is generated in the xenon cell. The intensity at each of the generated ultraviolet wavelengths depends on the relative phases and therefore on the temporal wave-form of the incident optical pulse. The Xe UV generator and the solar-blind photomultiplier are used for the correlation measurements.

The synthesized temporal waveform is characterized by using nonresonant four-wave frequency mixing to the ultraviolet as a nonlinear detector. The Raman sidebands mix in xenon to produce six generated ultraviolet frequencies. By changing the relative phases of the incident Raman sidebands with the liquid crystal array, they are then able to coherently control the dipole moment of the medium and are able to change the ratio of the intensities of the generated ultraviolet wavelengths. By choosing phases that maximize the four-wave mixing signal at all ultraviolet frequencies, they form the shortest pulse that this spectrum may make. The pulse width and shape are determined by electronically synthesizing two pulses, which are cross-correlated.

Varying the Degree of Coherence of Laser Light Produces Reduction in Diffraction
A. A. Maradudin, University of California at Irvine

A team of physicists, conducting a closely coupled theoretical and experimental effort, have demonstrated that rather unusual optical effects can be produced by manipulating the degree of coherence of the laser beam passing through surfaces whose asperities are specifically designed according to a first principles analytical theory and manufactured to produce exactly such a distribution of asperities. A striking new finding is that by combining such secondary sources in a Mach-Zehnder interferometer setup, they have produced an order of magnitude less diffraction of the resulting optical beam, in precise agreement with their theoretical prediction. The secondary source that was produced by passing the laser beam through such a "roughened" optical phase plate glass, changes the laser beam coherence thereby producing a so called "secondary Shell-Model source," which has been known to have rather unusual beam propagation properties. This group is further studying such effects for optical tagging for IFF as well as for tracking the target in real time, simultaneously conducting optical communication of the beam in a secure mode. The physics of this frontier area also directly correlates with what is known in condensed matter physics as the phenomenon of "Universal Conductance Fluctuations." Therefore it is projected that this area of study offers an exciting new frontier.

Plasma Instability in a Quantum Well Structure for THz Radiation Generation
P. Bakshi, K. Kempa, Boston College
E. Gornik, Technical University of Vienna, Austria

The basic idea for THz generation via plasma instabilities in QW structures was proposed by Bakshi and Kempa in 1997, and further elaborated in 1999 and 2000. Subsequent theoretical and experimental progress has now led to a demonstration of this phenomenon. Theoretical considerations had shown that an interaction of an emission mode with an absorption mode would lead to a plasma instability (1997). Quantum well structures were specifically designed (Vienna) to achieve appropriate conditions for the realizations of this phenomenon, and experimental signatures have been obtained which demonstrate this phenomenon. The theoretically predicted phenomena were a) line width narrowing and b) invariance of frequency with bias. Both these features have been experimentally confirmed recently.

A more striking result is the appearance of a very sharp line, indicating that they are very close to the plasmon laser condition (see figure 3). The physical mechanism here is the *collective* interaction of the electrons on all the relevant energy subbands. This is quite different from the conventional cascade laser, a *single electron* mechanism. The collective interaction which forms the basis of this new phenomenon leads to coherent radiation in the THz range for suitably designed QW structures. Such a novel THz source will have many DoD and civilian applications such as detection and imaging.
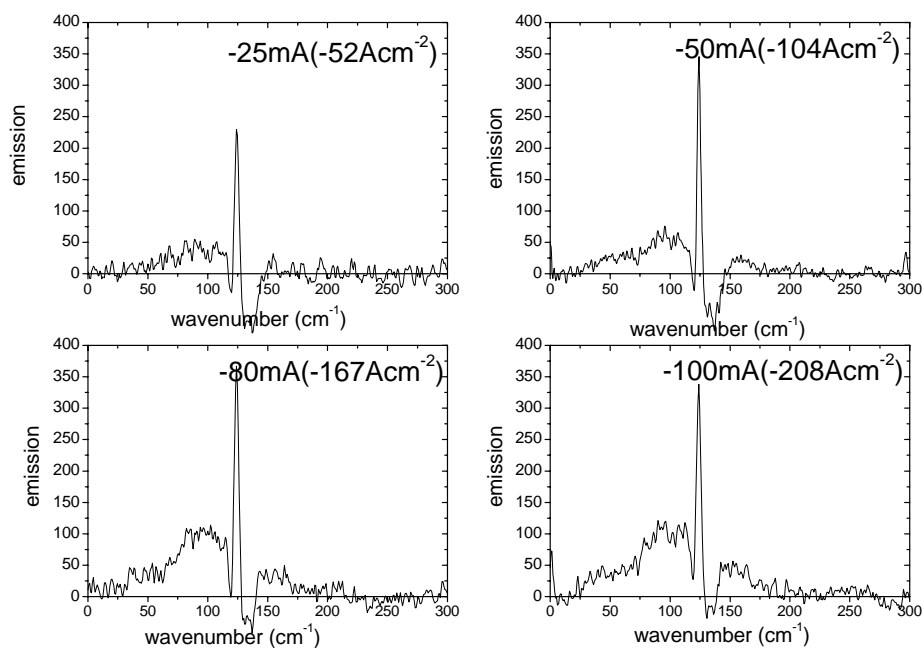
Figure 3. Plasma Instability in a Quantum Well Structure for THz Radiation Generation

Resonant Acoustic Phonon Generation in Doping Superlattices by Pulsed Far-Infrared Laser Radiation

Thomas E. Wilson, Marshall University, Huntington, WV

The goal of this project is to generate coherent phonons. A particular application for nano-microscopy has been submitted for a patent, but a host of other applications are envisioned. The apparatus, which is being put together, is rather complex. Nevertheless, significant progress has been made in the various components for it. Below we discuss these.

During the past six months they have succeeded in patterning, upon platelets cut from the superlattice-bearing Si:B wafers, the necessary thin metallic films on the front and back surfaces. The thin films consist of a small-period niobium grating coupler on the front surface, and a granular aluminum bolometer bridging two Cr/Au contact pads on the rear surface. The expected superconducting transition temperatures have been verified for both the Nb and granular Al films, and furthermore, similar (but larger) bolometers (fabricated earlier at the MPI-Stuttgart) have been demonstrated to be sensitive detectors of longitudinal acoustic phonons (generated from the optical absorption in thin granular aluminum films on the front faces of identical substrates of sub-nanosecond laser pulses at 532-nm) with approximately a five nanosecond resolution. The bolometer electrical response is nicely coupled out of the cryostat by a miniature broadband transmission line transformer with GHz-bandwidth. They have also had machined a 3-m long corrugated waveguide appropriate for use at 250 GHz, for the beam transport of the cavity-dumped

THz laser radiation to a floor-mounted liquid helium cryostat. The patterned platelets remain to be diced and lapped into smaller samples appropriate for the cryogenic stress-apparatus for phonon spectroscopy (to verify the expected monochromaticity) of the phonons generated by the THz laser radiation in the doping superlattices. The PI hopes to demonstrate coherent form of phonon generation by early spring.

MURI Topic: Giga-Hertz Electromagnetic Wave Science and Devices for Advanced Battlefield Communications
Zbigniew Zelinski, University of Colorado, Colorado Springs

In June 2004 a team of researchers initiated work (experimental and theoretical) on materials and devices operating at high frequencies. A few highlights of their work are listed below.

They have worked on optimization of Fe-based band-stop filters. They used Fe/Cu multilayered film in microstrip filters to demonstrate the feasibility of narrow-band magnetically tunable stop-band planar microwave devices. They observed considerable narrowing of the stop band and determined that this was due to the breaking of Fe films by Cu interlayers, which is expected to reduce the typical grain size. A second method to reduce the width of the stop band is to reduce the thickness of the metallic magnetic layer, thus reducing eddy currents. The tuning frequency of the filter extends from X band to K band with a magnetic field up to 4 kOe. This way of integrating Fe films in guided wave structures opens the road to a new generation of miniature size low-cost tunable planar microwave devices with MHz linewidths.

Some of the team have studied the excitation of magnetic surface plasmons on an artificial magnetic metamaterial at microwave (10 GHz) frequencies. The magnetic metamaterial consists of split ring resonators (SRRs), similar to those used in negative index metamaterial samples. The method used to probe the magnetic plasmons is identical to that used to study magnetic surface waves on FMR samples; that is, a prism is used such that an incident microwave beam undergoes total internal reflection (TIR) at an interface. On the other side of the interface is placed the SRR sample, and the frequency spectrum taken of the beam reflected by the prism. Because of the interaction between the sample and the prism, there is a pronounced attenuation in the reflected beam where the surface plasmon is expected to exist. Numerical simulations confirm the frequency location of the plasmon, and also predict the observed resonance features in the reflection spectrum.

Work has progressed on the development of the linear and nonlinear theory of microwave signal processing devices using spin waves in magnetic samples of restricted geometry. A prototype for 5/10 GHz of nonlinear microwave signal processor device is currently under construction. In addition, the magnetostatic spin wave modes in magnetic ribbons of rectangular cross section are being studied, since such structures may prove particularly useful for high frequency applications. Earlier they developed an innovative new theoretical approach to this class of problems, based on application of the extinction theorem of wave propagation theory. Their past method, however, could be applied only

to ribbons whose cross section has a rather modest aspect ratio. They have formulated a new approach within the general scheme, which now allows one to address aspect ratios as large as 100 to 1, and obtain exact (numerical) results. Calculations are actively underway

MURI Topic: Solitonic Information Processing
George Stegeman, University of Central Florida, CREOL

The principal goal of this MURI program – which is in its last year of support – is to use soliton interactions to do computation and signal processing. The effort to achieve these goals has been focused on uncovering the basic underlying science responsible for spatial (in contrast to temporal) solitons and their interactions. In particular, the MURI research team has discovered and explored many different types of spatial solitons, collisions between them, and interactions within soliton or waveguide arrays. In the process of these investigations, this MURI program has achieved a number of "firsts" in spatial soliton science and its application.

For example, the research team has pushed the frontier by predicting and observing many different types of spatial solitons. These include the first experimental observation of 2D lattice solitons (Nature 422, 147, 2003); first experimental observation of spatial gap solitons (PRL 90, 023902, 2003); first experimental observation of vortex lattice solitons (PRL 92, 123904, 2004); discovery (PRL 92, 223901, 2004) and observation (submitted to Nature) of random-phase (incoherent) lattice solitons. In addition, the first experimental observation of elliptic incoherent solitons (Opt. Lett. 68, 1248, 2004); prediction of 2D composite solitons (PRL 84, 1164, 2000) and their first experimental observation (Opt. Lett. 25, 1113, 2000); the prediction and first observation of rotating "propeller" solitons (PRL 87, 143901 2001); and holographic solitons (Opt. Lett. 27, 2031, 2002). Below is the first observation of a spatial soliton in any periodic 2D structure. Figure (4a) shows normal diffraction when a beam of several microns in diameter strikes a periodic array of waveguides in a SBN:75 crystal. Figure (4b) shows the formation of a soliton when the nonlinearity is added; while Figure (4c) shows a very good comparison with theory. This is one of many important steps in soliton computing since it uncovers the rules of engagement between many solitons interacting in computational configurations.

Figure 4.

(4a) Lattice Diffraction (200V)	(4b) 2D Lattice Soliton (800V)	(4c) Soliton simulation
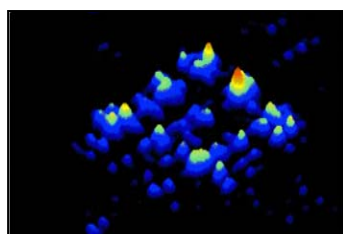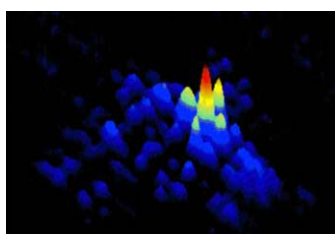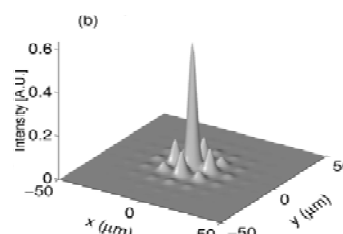
The MURI team has also been first at evolutionary new concepts in discrete soliton networks or waveguide arrays. For example, the team has discovered incoherent modulation instability (MI) (PRL 84, 467, 2000) and made the first experimental observation of incoherent MI (Science 290, 495, 2000); first observation of white-light MI (to appear, PRL); first experimental observation of discrete modulation instability (PRL 92:1639021-4, 2004); and the first observation of nonlinear optical beam interactions in waveguide arrays (PRL 93:939031-4, 2004). These experiments take another important step toward soliton computing since computation will involve the collision between many solitons and consequently be subject to these instabilities. These experiments therefore provide the understanding necessary to either avoid or take advantage of these inherent instabilities. Figure 5 below shows the first observation of modulation instability in a 1D array of waveguides. As the intensity is increased from figure 5(a) to 5(b), the optical transmission through the AlGaAs waveguide array develops a periodic modulation whose frequency is a function of the incident intensity or, since this is a Kerr medium, the nonlinearity.

Figure 5. Modulation instability in a 1D array of waveguides
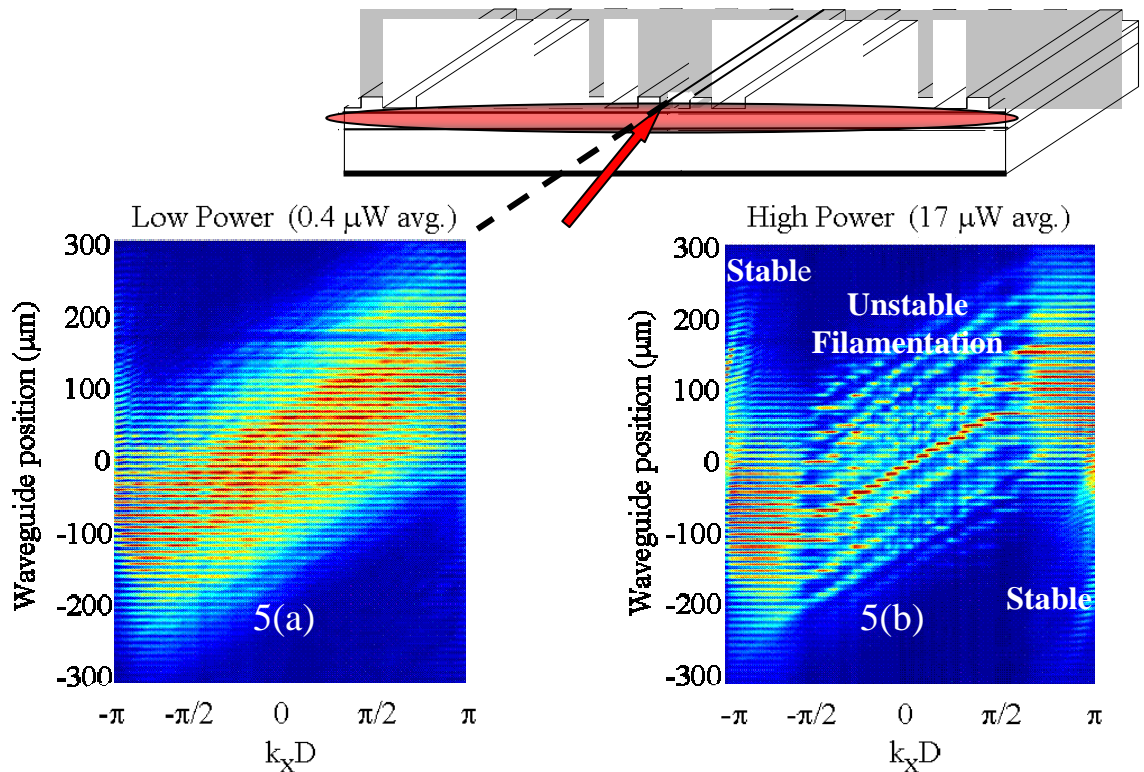
In addition, the MURI team has also been first at a number of experiments that involves multiple collisions between vector solitons. The idea is to develop a vector algebra that is important to any soliton computation scheme. For example, the team carried out the first

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \times \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} b \\ a \end{bmatrix}$$
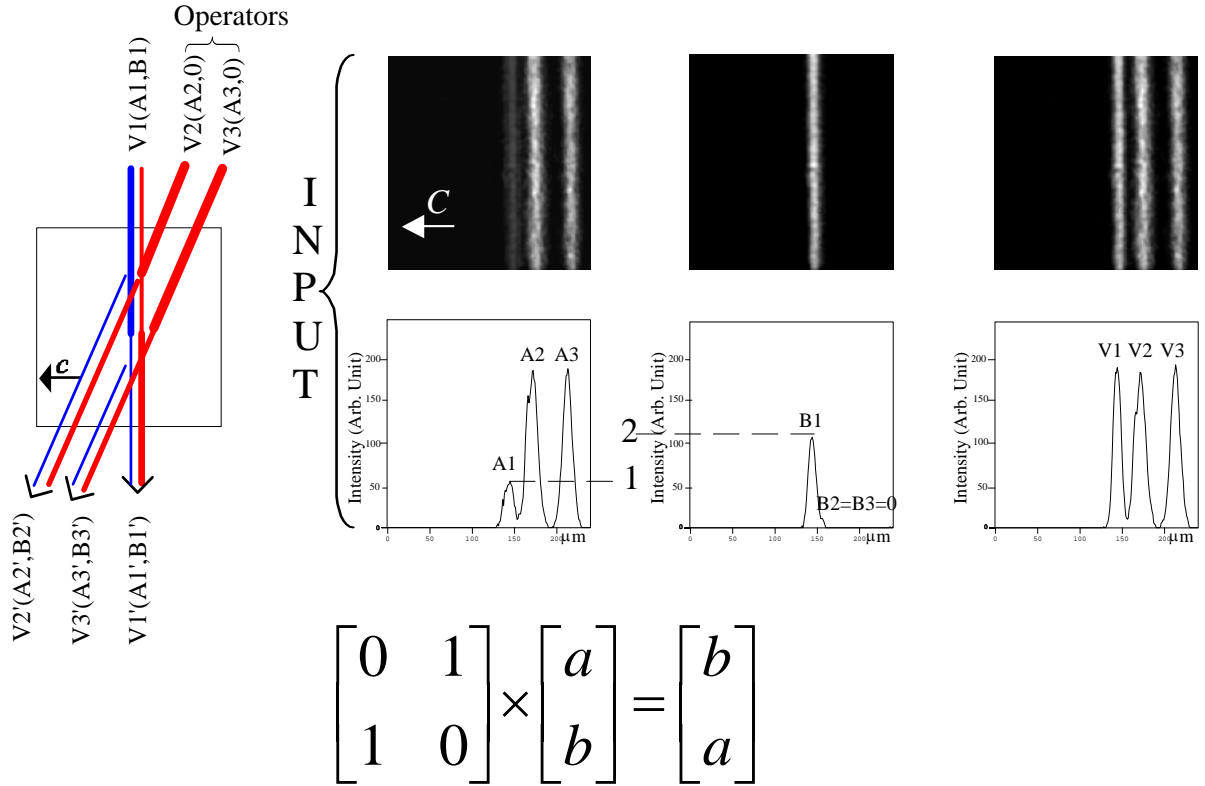
Figure 6. Two collisions can reverse the *a* and *b* components of a vector soliton..

experiments with information transfer via cascaded collisions of vector solitons (Opt. Lett. 26, 1498 2001), first fixing experiments resulting in directional couplers and splitters (Opt. Lett. 26, 1274, 2001) and a host of experiments that increase the number of soliton collisions to three and four vector solitons which have their *a* and *b* vector components of a vector altered while keeping each vector magnitude constant. In the figure 6 above, one sees that two collisions can reverse the *a* and *b* components of a vector soliton. In this way, two vectors act as the inverse matrix that operates on a vector.

Yet another area in which the MURI team has accomplished a number of firsts is in the use of a waveguide array to transport and direct information along a waveguide array. They had previously proposed and analyzed a radically new approach to 3D optical circuitry with routing determined by spatial soliton control. The general idea is shown below in figure 7. The figure represents discrete parallel waveguides directed down into the page. The signal moves along a path via discrete solitons due to evanescent field coupling between adjacent waveguides. Earlier work has shown that strongly confined solitons can be used to direct or block the signal around the network. In this experiment they have demonstrated for the first time the use of an independent beam as a "block."

That is, as light is transported across the waveguide array, the transport is stopped when the control beam excites or blocks transmission through that waveguide.

It is clear that the goal of "reconfigurable interconnects" for signal processing, routing, etc., has now been achieved, which is a major breakthrough. When taken together, these demonstrations make clear that while the potential for solitons to act as computation devices is real, and while that significant progress has been made to reaching this goal, much work still remains to be done.

AlGaAs array

Result of Single Experiment

Observation Plane

1. Deflect signals by a blocker" into a different path

2. "Move" a blocker optically to neighboring channels
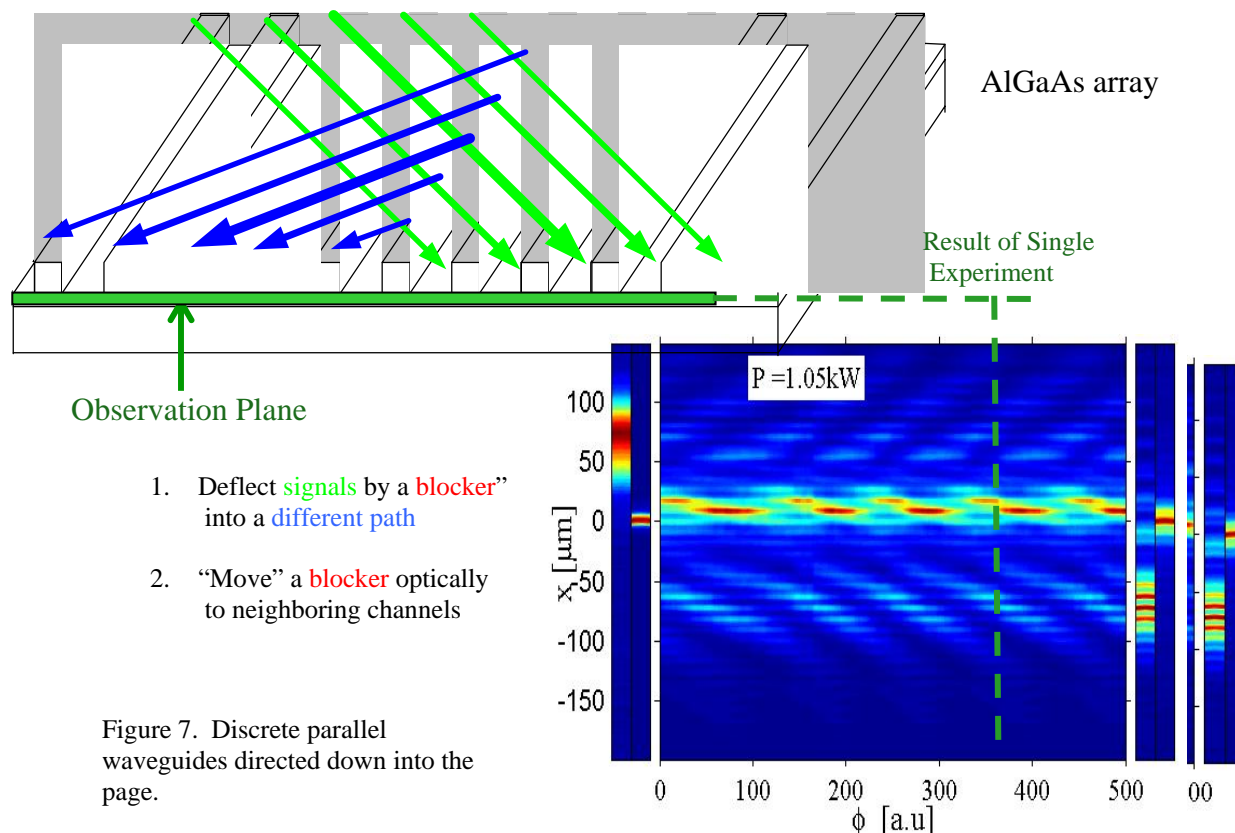
Figure 7. Discrete parallel waveguides directed down into the page.

Quantum Well Interference Fringe Experiments
S. Mosor, J. Sweet, B. Richards, G. Khitrova, C. Ell, and H.M. Gibbs
Optical Sciences Center, University of Arizona, Tucson, AZ 85721

Researchers at the University of Arizona are studying the conditions for seeing interference fringes using photoluminescence emitted from opposite sides of a quantum well [1]. The lack of translational invariance perpendicular to the plane of a single quantum well causes equal probability for spontaneous emission to the left or right. Combining one emission path from the left and one from the right into a common detector leads to interference fringes for fundamentally indistinguishable paths corresponding to a V-shape geometry with the same in-plane photon momentum [1]. For all other paths, no interference fringes are observed. See figure 8. For example, if emissions into opposite directions are interfered, fringes are observed only when the

direction is normal to the quantum well; i.e. a mere tilt of the sample relative to the detection directions destroys the fringes. The sample (DBR55) was a single InGaAs/GaAs quantum well with 1s photoluminescence occurring at 844 nm. The excitation was by a cw He-Ne laser beam (1 mW, 632.8 nm) focused to about 100 μm.

They also used samples with four quantum wells with spacings d in the vicinity of Bragg ($d = \lambda/2$) and anti-Bragg ($d = \lambda/4$), where λ is the emission wavelength in the medium. In the vicinity of Bragg spacing, they find a clear maximum with a visibility very close to that of a single quantum well; see figure 9. As d is decreased below $\lambda/2$ the condition for optimum constructive interference between quantum wells is no longer met, and the contrast goes down. For spacings close to $\lambda/4$, the interference pattern is completely suppressed, because the roundtrip phase between adjacent quantum wells is π, resulting in destructive interference. Decreasing d below $\lambda/4$, moves away from the exact overall cancellation between the quantum wells and the contrast increases.

The same fringe disappearance away from the V geometry was observed for higher temperatures, lower carrier densities, and using a sample (DBR61; 880 nm) with increased disorder. There was no change in behavior in DBR55 (DBR61) up to a temperature of 50K (120K) where the photoluminescence becomes too weak to go higher. In [1] the carrier density was about $100/\mu m^2$; they find the same V-geometry behavior for carrier densities of $10/\mu m^2$ and $1/\mu m^2$ at 5K. They found no wavelength dependence of the contrast observing fringes through a spectrometer. [1] W. Hoyer, M. Kira, S.W. Koch, H. Stolz, S. Mosor, J. Sweet, C. Ell, G. Khitrova, and H.M. Gibbs, "Entanglement between photon and quantum well", Phys. Rev. Lett. 93, 067401 (2004).
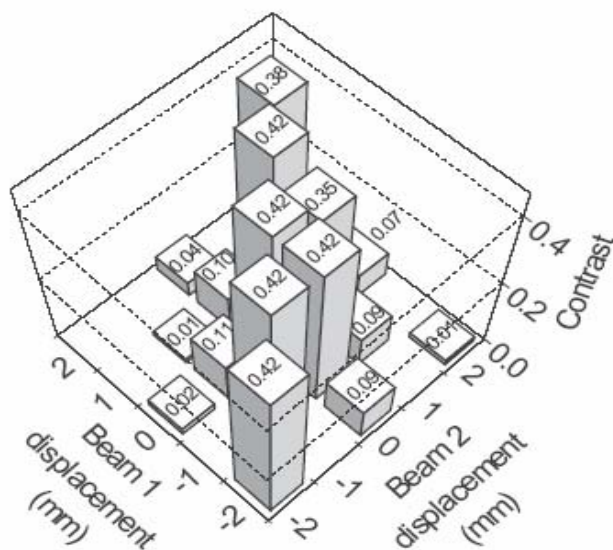
Figure 8. Dependence of fringe contrast on the directions of the two paths traveling in almost opposite directions as determined by the shift of the apertures along the y direction perpendicular to the interferometer plane. Opposite signs of displacement correspond to tilting the sample by an angle φ (1 mm amounts to φ = 1.8°); equal signs to the V configuration.
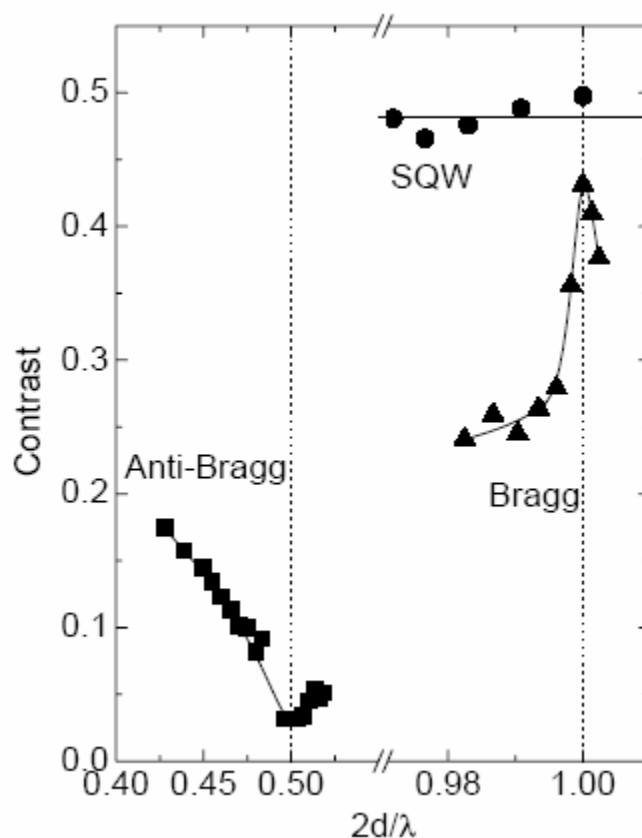
Figure 9. Dependence of fringe contrast on the separation d between quantum wells. Due to their MBE process, layer thickness *t* decreases with increased radius r on a sample. This allows them to tune through both d = λ/2 (Bragg) and *d* = λ/4 (anti-Bragg) using two samples, with the Bragg (anti-Bragg) position determined by reflectivity maximum (minimum). Relative *d* values were obtained using *t(r)* determined by measuring the radial dependence of the single mode of an empty microcavity. A clear contrast maximum for Bragg and minimum for anti-Bragg spacings are observed. The lines are guides to the eye. The single quantum-well contrast is independent of position on the sample; *d* for it is merely the thickness of the cap layer.

Low-Voltage, Magnetically-Actuated Optical Phase Modulators
Alan Kost, Optical Sciences Center, University of Arizona

There continues to be interest in low cost optical modulators for applications in information technology (e.g. optical communications and optical data storage). The most widely used modulators (e.g. $LiNbO_3$ electro-optic type) are expensive. Optical modulators that use reflective membranes that move under electrostatic or magnetostatic forces have potentially lower cost. The electrostatic type has received considerable attention. The electrostatic approach requires a drive voltage of 40 volts or more and is not directly compatible with silicon VLSI, which can supply about 1 V or less. This program is investigating optical phase modulators with reflective membranes that are magnetically controlled and can be driven by lower voltages. So far, they have been able to reduce drive voltage to about 4 volts. The modulator can be constructed entirely on a

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semiconductor chip, scaled to micron dimensions, and fabricated with conventional processes.
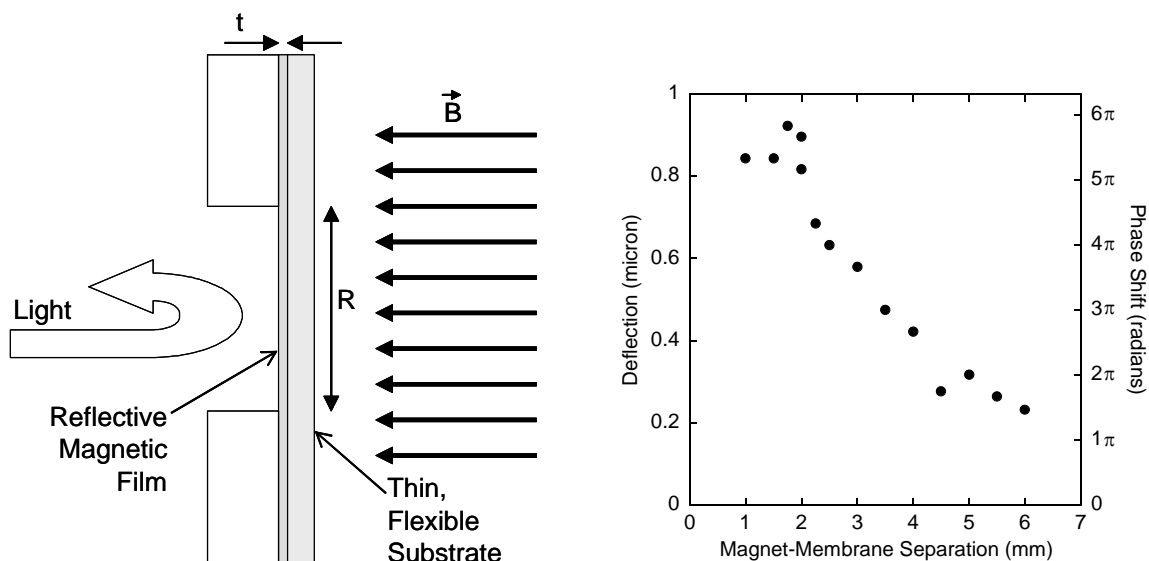
Figure 10.

Nanoshell-based Infrared Adaptive Materials
Naomi Halas, Rice University

Nanometer-scale structures that are optically active at the visible and infrared wavelengths are applicable to a very broad range of technologies such as pigments, telecommunications, biotechnology, sensing and photovoltaics. To have a single material system whose optical activity is tunable over the range of visible and infrared wavelengths is advantageous for advancing technologies in all of these fields. Such a material system was a major goal of the Nanoshell-Based Infrared Adaptive Materials MURI, which has just completed its final year. This MURI team developed fabrication techniques and demonstrated a material system whose optical response is tunable from visible wavelengths to nine microns. The technique is based on the plasmon response of ultra-thin metal films. The wavelength at which the plasmons resonate with optical fields is largely independent of the metal but varies widely with the size and shape of the film. A nanometer-scale metal shell, or nanoshell, will have a plasmon response on both the outer and inner surfaces, each with its own resonant frequency. These two plasmon modes interact resulting in an overall response of the nanoshell to incident radiation with a different resonant frequency. By choosing the thickness and size of the shell, the interaction of the two modes can be chosen and the optical response is controlled. Further tuning can be reached by nesting several nanoshells. Using this technique, the material frequency response can be readily tuned from visible to nine microns by design.

Theoretical research has accompanied this experimental effort and developed a simple physical model of plasmons in nanoshells and a highly acclaimed finite difference time domain (FDTD) code for extensive simulations. The physical model of plasmon interaction in nanoshells is analogous to electron orbital hybridization in molecules. It is a simple model and is a major contribution to the design of an optically responsive material based on nanoshells. The FDTD code represents the most advanced code for analyzing the plasmon response of arbitrarily-shaped metal objects in an optical field. A final goal is to provide a graphical user interface to this code. This is a powerful tool for the development of plasmon-based structures such as optimized substrates for surface enhanced Raman spectroscopy.

The overall goal of the MURI was to "develop a breakthrough technology that will enable the control and manipulation of infrared radiation with unprecedented precision, based on components that can by ultimately produced *en masse* and at moderate cost." This goal was largely met with the theoretical design tools and experimental techniques that resulted from this project.

V. TECHNOLOGY TRANSFER

Imaging Infrared System with Extended Depth of Field Focusing

The objective developed from research performed at the University of Rochester. It is expected to demonstrate an innovative optical detection and imaging system that will allow battlefield imaging through smoke, dust and fog obscurants in the 10 micron wavelength range. The Phase I effort will deliver a feasibility concept design and a prototype instrument. The system employs a multi-mode, diffraction limited, infrared telescope that can operate either in a passive mode or in an active mode using 10.6 micron laser illumination. This is the first system of its kind including the following innovative capabilities: 10 times improvement in the depth of field as compared to standard optical systems (see discussion below), uncooled microbolometer array for ease of operation, elimination of cat's eye reflection, use of narrow band filter in the active mode of operation to improve signal to noise performance, and computer controls for automated operation. The final system will be small, portable and designed for battlefield environments. The primary optics is 10 inches in diameter. Low cost is achieved through small size and use of state of the art, commercially available components. The system is designed to operate in the range from 500 feet to 10 miles with a minimum of focus adjustment required because of the extended depth of field capability. Significant applications for the system are envisioned for the DoD Components and homeland security.

Advances in optical and digital image processing systems have led to extend depth of field capability. N. George and W. Chi have developed a system that extends the depth of field by a factor of ten over conventional systems [Wanli Chi and Nicholas George, "Electronic imaging using a logarithmic asphere," Opt. Lett. 26, 875-877 (2001)]. Figure 11 below shows results for the new system compared to a high quality Nikon lens system.
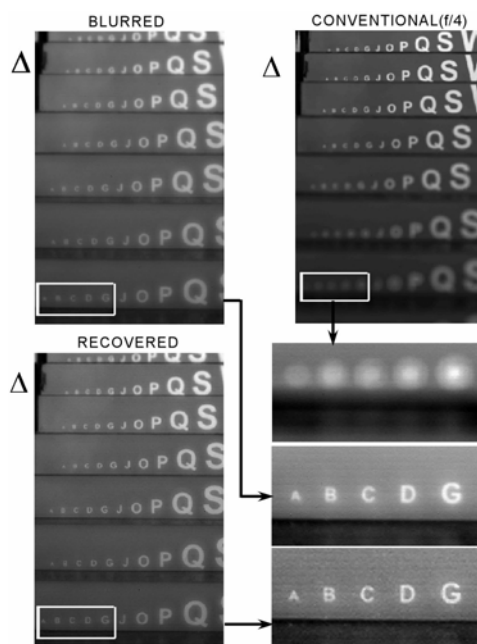
Figure 11 shows the experimental results using the log asphere and linear digital processing. The test object used in this experiment is a staircase object, with variable size letters attached to each step riser. The distance between neighboring step risers is 50mm. The nominal f/# of the lens is 4 and focal length is 60mm. The detector pixel size in the experimental setup is $23\mu m\times23\mu m$, so the resolution is limited by CCD pixels. Shown in the upper left is a picture taken using the logarithmic asphere. The linear digital processed image is shown at lower left. At upper right is the picture taken with Nikon lens using same focus and f/# settings. The object position denoted with Δ has a distance of 950mm to the lens, the best focused object plane. Each step down is 50mm closer to the lens. The depth of field of the Nikon lens is $\pm23mm$, so the depth of field of the new system is 10 times larger than the conventional lens. In the lower right are magnified pictures of the images for a better view.

Nanoshell-based Infrared Adaptive Materials
Naomi Halas, Rice University

In 1999, a new MURI began on the study of nanoshells to develop nanoshell-based materials with a designed optical response at the visible and infrared wavelengths. This MURI team was highly successful and a new company, *Nanospectra Biosciences, Inc.*, was established in September 2001 as a result. The purpose of this company has been to commercialize virtually any technology based on nanoshell materials, but has focused on biomedical applications. The company holds seven patents through Rice University: two for the nanoshell materials themselves and five for their applications including imaging, cancer and immunoassays. The biomedical application of nanoshells is a natural extension: the nanoshells are non-toxic, can be designed to have an optical response at wavelengths to which biological materials are largely transparent, and can be functionalized to target specific tissues. Preliminary research done in collaboration with Jennifer West of Rice University has been remarkable: in one study, tumors in mice were non-invasively eradicated with 100% success using nanoshells developed by the MURI

team. *Nanospectra Biosciences, Inc*. is aggressively pursuing this and other applications, and is making remarkable progress.

Transparent electronics
John Wager, Oregon State University, Cornwallis

Transparent electronics is a nascent technology involving the realization of invisible electronic circuits. Major MURI accomplishments to date in this area are described here. Transparent thin-film transistors (TTFTs) have been fabricated by ion beam sputtering, RF magnetron sputtering, and spin-coating deposition of ZnO channel layers. A TTFT with a SnO_2 channel layer was demonstrated; this device is potentially useful as a novel gas sensor. A new class of high-performance TTFT channel materials was identified; these materials are amorphous, multi-component oxides composed of heavy-metal cations. TTFTs fabricated using these materials as channel layers exhibit high mobility compared to amorphous Si TFTs, even when these layers are deposited at near room temperature. A number of patent applications have been filed, and the technology is expected to transition to the commercial sector. The results have been widely recognized as being highly significant for the next level of integration of optics with electronics, with potential for many new advanced optoelectronic devices. The results are also very important for the MURI on Intelligent Luminescence which will use a complex set of superposed optoelectronic components in pixel level integration for a corticonic (simulating human cortex functions) form of intelligent information processing. The Army needs such transparent electronics to implement pixel level adaptive information processing and to achieve a mimicking of cortical brain functioning for feature extraction. Therefore, this achievement is very timely for the MURI project.

Enhanced Backscattering of Laser Light for Target Identification, Tracking and Secure Communication
Zuhan Gu, Surface Optics Corporation

DARPA has initiated a program on optically tagging targets at very far distances, with the added attribute that the optical beam must carry secure optical communication and retrieve collected information. Our core program already has had these goals for more than a decade, and thus we had previously investigated what is called "Enhanced Retroreflection of Light." Also known as the "Halo Effect" and observed centuries ago, this phenomenon was only explained in detail by ARO PIs about a decade ago, combining analytical theory and experiments. Explanation of the precise physical origin of the phenomenon was so successful that new aspects of the phenomenon could be predicted, observed, and explored. That work had led to theoretical methods to structure the roughness of the reflecting surfaces and to produce the surfaces experimentally. Within the last year, it was demonstrated that the retroreflection of the light could be achieved at any desired angle of incidence with appropriately designed and manufactured surface roughness statistics. However, attendant with the desired beam was a specularly reflected/enhanced component – undesirable for the desired applications. Just recently it has been demonstrated that the enhanced retroreflected beam of laser light can be made to occur only at the desired incidence angle without the specular component. This

breakthrough will make it possible to replace the mini corner cubes that the DARPA project has had to rely on thus far. The resulting improvement to signal processing is rather dramatic, especially since it was also demonstrated that it is possible for a partially coherent laser beam to penetrate a turbulent atmosphere with improved S/N recovery of the information on the beam (an ARL accomplishment). Thus the ARL and ARO projects have become fused together, and will able to be transitioned to DARPA soon after the STTR Phase II project with Surface Optics Corporation ends.

Supra-nonlinear Nano-particulate Liquid-crystalline Optoelectronics
Dr. Nelson Tabirian, BEAM Engineering for Advanced Measurements Co.

Work carried out under our PI I. C. Khoo had been transitioned to BEAM Engineering for Advanced Measurements Co. via an SBIR. The science that was transitioned was the first observation of extremely high optical nonlinearity. In addition, the PI has shown that it is possible to achieve extremely high photonic sensitivity accompanying such high optical nonlinearity, thus opening up a new frontier of high sensitivity optics or optoelectronics. The central idea is to embed reconfigurable nanostructures within the optical medium – in this case liquid crystals – which will reconfigure themselves in response to externally applied fields. This was demonstrated by the PI, leading to a set of reconfigurable optical components, such as lenses, modulators and the like. More recently they have demonstrated the following:

1. Recording optical data 1000 times faster than it is done presently for CDs or DVDs. This will shorten the recording time of a DVD to seconds, which should make it useful for a number of new applications.

2. A "naturally occurring" liquid crystalline photonic bandgap material, a cholesteric liquid crystal. With their photosensitive (supra-nonlinear) liquid crystals they have demonstrated an unprecedented shift in the position of its Bragg reflection band under the influence of radiation. This paves the path to photo-tunable filters, mirrors with photo-tunable spectral properties and photo-switchable polarizers. All this work marks steps forward to one of their ultimate goals: universal spatial light modulators.

They are currently preparing patent disclosures. In the past they have demonstrated their ability to work with other companies synergistically. Already in Phase I they have made such contacts on this effort as well. Therefore this effort is bound to produce a new genre of optical components with numerous applications.
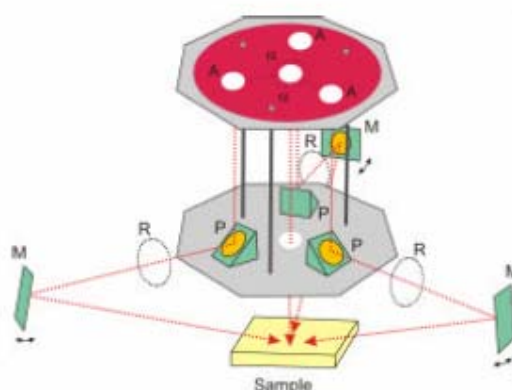
Figure 12   Optical holographic set up for making large area nonlinear and tunable polymer-LC 1-D, 2-D and 3-D photonic crystals.
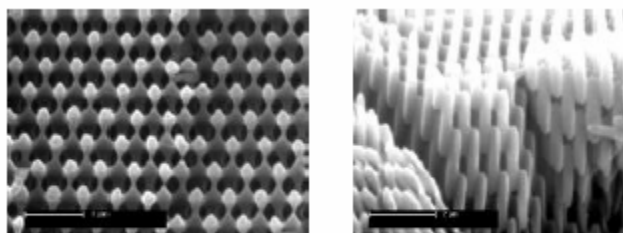
Figure 13   3-D photonic crystalline structures made with photo-resists [³].

MURI Program: Soliton Signal Processing
Paul Prucnal, Princeton University

An all-optical solitonic signal processing approach has been transitioned to industry. Over the course of this work there has resulted a portfolio of approximately 15 patents issued or pending, and a number of licenses of these patents to a small business, Kailight Photonics, Inc. Kailight's product called the "TASR" uses the patents on the Terahertz Optical Asymmetric Demultiplexer (the "TOAD") to do all-optical signal regeneration at 40 Gbits/sec. In June, Kailight partnered with Sanmina-SCI Inc, based in Dallas, to manufacture their products, and during September, has teamed up with the Heinrich Hertz Institute in Germany, to do 40 Gbit/sec transmission testing. A number of other companies are currently negotiating licenses for the TOAD in other applications areas, ranging from ultrafast sampling for instrumentation, to analog-digital conversion for broadband wireless communications.

The heart of this technology, the TOAD device shown below, can be used for processing conventional non-return-to-zero (NRZ), return-to-zero (RZ), or soliton signal formats. It consists of an optical interferometer, either in a loop (shown below) or Mach-Zehnder

geometry. It includes a nonlinear optical element such as a semiconductor optical amplifier (SOA). The injection of a control pulse induces an index change in the SOA, which causes a momentary change in the phase of the counter-propagating optical pulses, and interference at the output coupler that occurs on a picosecond time scale.
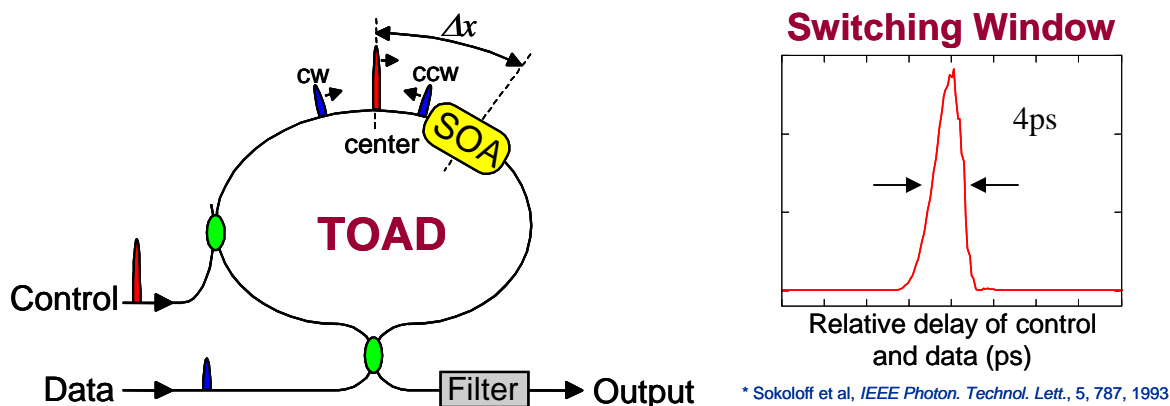
Figure 14. The TOAD is a spatio-temporal interface between soliton data transmission and a soliton-based computer. It is used for all-optical signal generation, for NRZ to RZ data format conversion, for wavelength conversion, and for 3R signal regeneration (re-amplification, re-shaping and re-timing). It is being explored if one can use the TOAD for header recognition and processing in all-optical packet switching or routing. It is likely that this device and its associated applications will have a substantial impact on the next generation of optical networks.

MURI Program: Ultracold Atom Optics for Inertial Navigation
Wolfgang Ketterle, Massachusetts Institute of Technology
Mark Kasevich, Stanford University
Dana Anderson, JILA, University of Colorado

An ARO MURI on Atom Optics that began in FY 2000 was deemed of such high quality by OSD that two teams were funded. The work was exceedingly productive, and progress has been reported here in previous years. Included was work such as "atom chip" technology and free-space interferometers. The device-scale "atom chips" actually transport *ultra-cold atoms* (not electrons!) via the magnetic fields created by the device configuration. Also designed here was an atom chip on which one could produce a Bose Einstein condensate. This will enable an easy-to-use standardized test bed for both future experiments and applications. The atom chip work was transitioned to ARL where work continues, both independently and in collaboration with the MURI team. Applications include unprecedented sensor capabilities such as improved atomic clocks for GPS, jam-proof navigation systems, covert navigation, underground structure detection, and mine detection. This work also addresses innovative approaches and capabilities in nanolithography. Science interests focus on coherently moving the cold atoms, and BECs, along the atom chips, wave guiding of the matter waves, coherently and reproducibly splitting the beams, and making atom-optic interferometers on a chip.

The potential to exploit this work for inertial navigation was recognized by DARPA with new funds in FY 2004. Atom optic based interferometers can afford such huge potential increases in sensitivity ($\sim 10^8$) that gyroscopes and accelerometers based on ultra-cold atoms cannot be overlooked. Thus DARPA together with ARO has begun the PINS (Precision Inertial Navigation Systems) Program. The goal is to rapidly develop the science that has grown out of the MURI into fielded inertial navigation systems. Industry partners are now working closely with Stanford and the University of Colorado to make robust components. University partners are working on all aspects of the science, including transporting and coherently splitting matter waves, and creating the needed diode lasers. For example, just this past month one of the atom chip experiments (MIT) achieved interference using a *condensate*. It was the first time on a microchip trap that a condensate was split in two halves that are spatially separated and still condensed. Interference is shown in the absorption picture of figure 15. We see the two halves of the condensate after time-of-flight expansion. This result was achieved after studying the release process from the magnetic trap and minimizing the unwanted 'kicks' imparted to the atoms when released. The splitting procedure still does not give a shot-to-shot reproducible pattern, meaning that despite the demonstrated interference, one does not yet have the control necessary for interferometry.
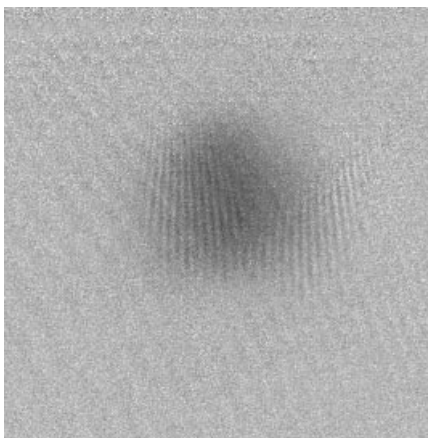
Figure 15. Absorption image showing the interference of the two halves of the condensate
released from the microchip.

VI. DIVISION STAFF

Dr. Peter Reynolds, Associate Director
Manages atomic and molecular physics programs.

Dr. Mikael Ciftan
Manages theoretical physics and nonlinear phenomena.

Dr. Richard Hammond
Manages optics, photonics, and image science programs.

Dr. Marc Ulrich
Manages condensed matter physics programs.

Monica Williams
Administrative Support Assistant

I. PROGRAM OBJECTIVES

The materiel assets of the modern U.S. Army are products of quantum leaps in science and technology of the recent past. The scientific community of the Army is obligated to remain aware of and be ready to exploit the continuing developments in science and engineering, if the Army is to remain the best equipped at minimum total cost of ownership in the future. During the past couple of decades, it has been universally recognized that advances in science and technology are also important engines of economic power. Consequently, in addition to the United States and Europe, who have been historically active in research and development (R&D), most industrialized countries, particularly Pacific Rim countries, are investing heavily in this area. They are experiencing remarkable growth of their industrial output and presenting increased competition to U.S. industry. The U.S. Department of Defense (DoD) is one of the largest investors in science and technology, and for efficient management of its R&D resources, must keep abreast of the important scientific developments globally.

As the lead agency responsible for supporting the Army in the areas of basic sciences and technology, the U.S. Army Research Office (ARO) maintains cognizance of important international scientific developments through its Far East Office (ARL-FERO) in Tokyo and the European Research Office (ARL-ERO) of the U. S. Army Research Laboratory, and the United States Research, Development, and Standardization Group-United Kingdom (USRDSG-UK). These offices are collocated with their respective foreign branches of the Office of Naval Research and the Air Force Office of Scientific Research, and they work very closely with each other in the spirit of RELIANCE. ARL-FERO is supported entirely by ARL and ARO. However, ARL-Europe is maintained by both ARL and the Army Materiel Command Office of International Cooperation as one of its two divisions; the other being the Standardization Division. ARO-Pan America (ARO-PA), located at the Army Research Office, Research Triangle Park, NC, covers activities in foreign countries in the Western Hemisphere. The primary objectives of ARO activities through these offices include identification of opportunities for leveraging unique expertise outside the United States, cognizance of emerging technologies available to augment the Army's R&D program objectives, and effective technology transfer to the Army laboratories, centers, and offices where possible.

II. MAJOR ACTIVITIES

Major activities of the three offices include:

- Keeping abreast of the important global developments in science and technology, which are then conveyed to the relevant elements of the Army and other interested DoD agencies. These offices also cosponsor international conferences that focus on areas of interest to the Army;

- Entertaining and evaluating proposals of original research of relevance to the Army's R&D program objectives, and supporting the selected ones through research grants, contingent upon the availability of funds. The progress reports are distributed to the laboratories, but, in particular, are sent to those who request Scientific Liaison and Scientific Cognizance, so that they can directly interact with principal investigators of these projects through correspondence and even exchange visits;

- Maintaining a rotational scientists program under which qualified Army scientists can visit selected foreign research institutions for assessment of the status of research in their area(s) of specialization by presenting seminars, or conducting short research projects, if invited by the host laboratory. Facilities are also provided to active Army scientists to present their original research at international forums and, conversely, to invite foreign experts to present seminars or conduct short-term projects at the Army laboratories where applicable;

- Organizing international workshops on important technical issues. In these workshops, selected active workers in the field, both from the Army laboratories (sometimes from other agencies also) and the host country are invited to participate. Books of extended abstracts and proceedings containing the summary of the deliberations and recommendations for future research and international collaboration are disseminated to the Army laboratories; and

- Responding to the inquiries and requests for assistance from the Army laboratories, Research, Development and Engineering Centers, and offices on special projects and technology assessment. These offices are also responsible for promoting cooperation and coordination with other international organizations and DoD agencies.

III. AREAS OF OPERATION

ARL-Far East Research Office (ARL-FERO) - Pacific Rim countries including Korea, Japan, China, Malaysia, Indonesia, Singapore, Australia, New Zealand, Thailand, Indian subcontinent, South Africa and Russia, in exceptional cases. ARL-FERO now is Asian Research Office, US Army International Technology Center – Pacific.

ARL - European Research Office- (ARL-ERO) - Western Europe, Central Europe, Eastern Europe, and Former Soviet Union countries, Middle East, Africa, and Southwest Asia.

CONFERENCE SUPPORT

The ARL-ERO promotes scientific and technical interchange by supporting and co-sponsoring a select number of international conferences, symposia and workshops that cover topics of special interest to the U.S. Army. The following conferences and workshops have received support in FY04. Meetings that received bi-service or tri-service DOD support are indicated by an asterisk (*).

ARL-ERO CONFERENCES

DATES (2004)	LOCATION	CONFERENCE/WORKSHOP TITLE/WEBSITE
1-5 October 2003	Acireale, Sicily, Italy	International Workshop "Physics of Light-Matter Coupling in Nanostructures
4-10 October 2003	Kyiv, Ukraine	Workshop on Remote Sensing Techniques and Instrumentation: International Cooperation
18-25 October 2003	Erice, Sicily	International School of Quantum Electronics, 39th Course – Microresonators as Building Blocks for VSL Photonics
20-24 October 2003	St. Petersburg, Russia	International Meeting "ARMOR – Medical and Technical Aspects of Antiterrorist and Rescue Operations"
4-6 November 2003	Lidingo, Sweden	Workshop on Secure IT and Vulnerabilities of Commercial Wireless Components
30 November – 4 December 2003	Ein Bokek, Israel	The 3rd Bi-National France-Israel Workshop on Biosensors, Biochips and Nanobiotechnology
23-25 February 2004	Rome, Italy	4th International Conference on Application of Conducting Polymers, ACP-4
29 February – 7 March 2004	Nizhny Novgorod. Russia	Scientific Workshop "Nonlinear Waves-2004"
6-7 May 2004	Trencin, Slovak Republic	The 6th Technical Conference "New technologies and materials used for production and repairs of defense equipment"
7-14 May 2004	Peradeniya, Sri Lanka	* Tenth Asian Congress of Fluid Mechanics
6-11 June 2004	St. Petersburg, Russia	Scientific Workshop "Partnership for Research and Development Collaboration
11-13 June 2004	Warsaw, Poland	Workshop on Optical Properties of 2D systems with interacting carriers
21-23 June 2004	Tirrenia, Pisa, Italy	Failure Modes in High-Value Engineered Systems – Phenomena and Modeling
29 June – 3 July 2004	St. Petersburg, Russia	4th Conference on Physics of Light-Matter Coupling in Nanostructures (PLMCN 4)
7-9 July 2004	Munich, Germany	2nd European Workshop on Structural Health Monitoring
11-15 July 2004	Cambridge, United Kingdom	Fifth International Symposium on Impact Engineering (ISIE5)
12-15 July 2004	Lisbon, Portugal	12th International Symposium on Applications of Laser Techniques to Fluid Mechanics
12-16 July 2004	Trieste, Italy	13th International Workshop on Laser Physics (LPHYS'04)
25-29 July 2004	Aveiro, Portugal	11th International Symposium on Solubility Phenomena – Including Related Equilibrium Processes
26-29 July 2004	Madeira, Portugal	International Conference on Computational and Experimental Engineering and Sciences ICCES'04

9-22 August 2004	Windsor, United Kingdom	The Third Windsor Summer School on Condensed Matter Theory "Field Theory of Quantum Coherence, Correlations and Mesoscopics"
22-24 August 2004	Delmenhorst, Germany	Auditory Scene Analysis and Speech Perception by Human Machine
29 August – 4 Septe 2004	Pecs, Hungary	* Technical Workshop on Toxicity for Biodefense
11-12 September 2004	Bertinoro, Italy	Views on Designing Complex Architecture (VODCA)
14-17 September 2004	Dnipropetrovsk, Ukraine	International Conference on Mathematical Methods in Electromagnetic Theory
28 September – 1 October 2004	Cantabria, Spain	EUROMECH Colloquium on Fibre-reinforced Solids: Constitutive Laws and Instablities
3-6 October 2004	Heraklion, Crete, Greece	13th European Workshop on Heterostructure Technology (HETECH 2004)
3-7 April 2005	Adelaide, Australia	Eighth International Conference on the Biogeochemistry of Trace Elements
10-13 April 2005	Oxford, United Kingdom	Gun Tubes 2005 Conference (GT2005)
19-22 June 2005	Nottingham, United Kingdom	Sixth International Conference on Military Geology & Geography

FOCUSED WORKSHOPS

22-23 January 2004	Edinburgh, United Kingdom	Foreign Body Detection Workshop
22-23 January 2004	Edinburgh, United Kingdom	Foreign Body Detection Workshop
5-7 April 2004	Karnataka, India	Workshop on "Emerging Trends and Recent Developments in Ceramics and Ceramic Matrix Composites"
10-11 May 2004	Montreux, Switzerland	International Workshop on MEMS and Nanotechnology (MNI): Applications
10-14 May 2004	Sofia, Bulgaria	Third International Workshop on Commercial Information Technology for Military Operations – CITMO 2004
13-17 May 2004	Almaty, Kazakhstan	International Workshop "Science and Engineering: Productive Forces in the Society"
21-23 June 2004	Tirrenia, Pisa, Italy	* Failure Modes in High-Value Engineered Systems – Phenomena and Modeling
24-25 June 2004	Bath, United Kingdom	International Workshop on Biologically Inspired Robots
27-30 July 2004	Morogoro, Tanzania	Scent detection by sniffer animals and electronic noses
27-30 July 2004	Morogoro, Tanzania	* Scent Detection Workshop
13-15 September 2004	Bled, Slovenia	* International Workshop on Physical Aspects of Multiscale Modeling
14-16 September 2004	North Berwick, United Kingdom	Concepts and challenges for integration in water resources management: an international forum" Workshop
19-23 September 2004	Kiev, Ukraine	* International Workshop on metal, metal-ceramic and ceramic protective coatings
27 September – 1 October 2004	Torremolinos, Spain	* Workshop on Security Applications of LIBS and 3rd International Conference on Laser Induced Plasma Spectroscopy and Applications (LIBS 2004)

ARL-ERO "SEED" PROJECTS

INVESTIGATOR/INSTITUTION	LABORATORY POC	SUBJECT
BROWN Imperial College, United Kingdom	F. Caradonna AMRDEC	The effect of Self-Induced Wake Blade Interaction on Helicopter Blade Sailing
ZHELTIKOV M.V. Lomonosov Moscow State University, Russia	M. Scalora AMRDEC	Spectral Transformation of Ultra-Short Pulses in Photonic-Crystal
KANDIDOV M.V. Lomonosov Moscow State University, Russia	M. Scalora M. Bloemer AMRDEC	Filamentation of a Femtosecond Laser Pulse in Optical Media: Towards Spatial Regularization of Multiple Filaments
GINI University of Pisa, Italy	R. Sims J. Mills AMRDEC	Statistical Analysis and Modeling of High Resolution Ground Radar Clutter and Targets
GORODESTSKY St. Petersburg Institute for Informatics & Automation of the RAS, Russia	R. Sims J. Mills AMRDEC	Unexpected Automatic Ground Object Recognition
WORM Swedish Defense Research Agency, Sweden	J. Sutton ARL-HRED	Investigating the Impact of Culture on Teamwork
TRIMBOS TNO Prins Maurits Lab, The Netherlands	R. Weiss ARL-SLAD	The effect of cleaning on the properties of NBC suits that have been contaminated with different chemical compounds
KINLOCH Imperial College London, United Kingdom	R. Shaw ARO	Nano-Composites: Relationships Between Nano-Structure and Mechanical Properties: Phase II
VOLOSHINOV M.V. Lomonosov Moscow State University, Russia	N. Gupta ARL-SEDD	Application of Single Crystals of Tellurium in Imaging AOTFs
RATCLIFF CISR, South Africa	B. LaMattina ARO BC Moran PEO Soldier	Experimental Assessment of Porous Screens for Protection of Vehicles and Humans from Blast and Shock Effects

E. ARL-FERO Conferences and Workshops

The ARL-FE promotes scientific and technical interchange by supporting and co-sponsoring a select number of international conferences, symposia and workshops that cover topics of special interest to the U.S. Army. The following conferences and workshops have received such support in FY02. Meetings that received bi-service or tri-service DOD support are indicated by an asterisk (*).

ARL-FERO CONFERENCES AND WORKSHOPS

DATES	LOCATION	CONFERENCE TITLE
7-9 Oct 2003	Seoul, Korea	* The 14th International Conference on Adaptive Structures and Technologies
8-13 Oct 2003	Yokohama, Japan	* 8th International Union of Materials Research Societies International Conference on Advanced Material Symposium
14-16 Oct 2003	Taipei, Taiwan	* 2003 IEEE International Carnahan Conf on Security Technology
29-31 Oct 2003	Tokyo, Japan	* The 9th Micro optics Conference
2-6 Nov 2003	Hawaii	*The Third International Conference on Light Materials for Transportation Systems (LiMAT-2003)
9-13 Nov 2003	Kyoto, Japan	* XVth International Symposium on the Reactivity of Solids (ISCS-03)
17-19 Nov 2003	Victoria, Australia	* Twelfth International Conference on Composite Structures (ICCS/12)
19-21 Nov 2003	Tokyo, Japan	* Japan International SAMPE Symposium and Exhibition
21-22 Nov 2003	Seoul, Korea	* Fifth China-Japan-Korea Joint Workshop on Neurobiology & Neuroinformatics
6-7 Dec 2003	Canberra, Australia	* The First Australian Conference on Artificial Life
8-12 Dec 2003	Canberra, Australia	* 2003 Congress on Evolutionary Computation
26-30 Jan 2004	Bangkok, Thailand	* WHO & Asia-Pacific Electromagnetic Field (EMF) Conference
11-13 Feb 2004	Taipei, Taiwan	5th Asia-Pacific Transportation Development Conference
14-16 Mar 2004	Gyeongju, Korea	* The 12th International Symposium on the Physics of Semiconductors and Applications (ISPSA-2004)
17-19 Mar 2004	JeJu, Korea	* Database Systems for Advanced Applications
29 Mar – 1 APR 2004	Fukuoka, Japan	* The 18th International Conference on Advanced Information Network & Applications
11-14 May 2004	Nara, Japan	* The 5th International Symposium on Laser Precision Microfabrication,
17-21 May 2004	Peradeniya, Sri Lank	The 10th Asian Congress of Fluid Mechanics
Jun 28 - Jul 2 2004	Wollongong, Australia	* The International Conference for the Science and Technology of Synthetic Metals (ISCM 2004)
19-23 Jul 2004	Cairns, Australia	* The 4th International Conference on Vacuum-Ultraviolet Radiation Physics (VUV14)
12-16 Sept 2004	Seoul, Korea	* The 31st International Symposium on Compound Semiconductors
29 Sept – 1 Oct 2004	Hong Kong	* IEEE/LEOS 1st International Conference on Group IV Photonics
22-26 Nov 2004	Chiang Mia, Thailand	* 25th Asian Conference on Remote Sensing and 1st Asian Space Conference
29 Nov – 1 Dec 2004	Melbourne, Australia	* 3rd International Conference on Advanced Materials Processing
13-16 Feb 2005	Melbourne, Australia	Decon Downunder – International Conference on the Removal or Destruction of Highly Toxic Chemical and Biological Contamination
28-31 Mar 05	Taipei, Taiwan	* The 19th International Conference on Advanced Information Networking and Applications (AINA-2005)

FOCUS WORKSHOPS

5-7 No 2003	Fukuka, Japan	The 4th International Workshop on Modeling in Crystal Growth
5-7 Apr 2004	Karnataka, India	Workshop on "Emerging Trends and Recent Developments in Ceramics and Ceramic Matrix Composites"
19-21 Apr 2004	Melbourne, Australia	* 2004 Frontiers of Structure Health Monitoring
11-13 May 2004	Jeju, Korea	* The 2nd Korea-US Workshop on Metallic Structural Materials
23-26 Aug 2004	Brisbane, Australia	* Insect Sensors and Robotics, A workshop at the Biology-Machine Interface
29 Sept – 1 Oct 2004	Hong Kong	* IEEE/LEOS 1st International Conference on Group IV Photonics
31 Oct – 1 Nov 2004	Osaka, Japan	* The first Workshop on Anisotropic S&T of Materials and Devices
16 – 17 Dec 2004	Melbourne, Australia	2nd Australasian Workshop on Structural Health Monitoring

Conference/workshop/symposium cosponsored by two or more services
† Postponed to current date because of SARS outbreak

ARO-FE "SEED" PROJECTS

Investigator/Institution	Laboratory POC	TITLE
M. K. Wu, Y. K. Hwu and C. D. Chen Institute of Physics, Academia Sinica, Taiwan	Rich Hammond ARO	* High resolution real time phase contrast radiology study of hydrodynamic in micrometer scale

IV. INTERNATIONAL STAFF

A. ARL-ERO Personnel

Dr. James Harvey

Director, ARL-ERO, and Chief Electronics, Physics, Math Branch
FPO AE 09499
Telephone: 011-44-207-514-4907
Fax: 011-44-207-724-1433
E-mail: jharvey@usardsguk.army.mil

Dr. Sreerangapatam Sampath

Chief Aeronautics and Mechanics Branch, ARL-ERO
FPO AE 09499
Telephone: 011-44-207-514-4904
Fax: 011-44-207-724-1433
E-mail: ssampath@usardsguk.army.mil

(Vacant) Chief Chemical, Biological, Materials Sciences Branch, ARL-ERO

Dr. Larry Murdock

Chief Aviation and Missile Applications Branch, ARL-ERO
FPO AE 09499
Telephone: 011-44-207-514-3141
Fax: 011-44-207-724-1433
E-mail: lmurdock@usardsguk.army.mil

Mr. Raymond McGowan

Chief Communications and Electronics Applications Branch, ARL-ERO
FPO AE 09499
Telephone: 011-44-207-514-4909
Fax: 011-44-207-724-1433
E-mail: rmcgowan@usardsguk.army.mil

Dr. Henry Catherino

Chief Tank, Automotive, Armaments Branch, ARL-ERO
FPO AE 09499
Telephone: 011-44-207-514-4217
Fax: 011-44-207-724-1433
E-mail: hcatherino@usardsguk.army.mil

Mrs. Joanne Paul

Tech Transfer Coordinator, ARL-ERO
FPO AE 09499
Telephone: 011-44-207-514-4933
Fax: 011-44-207-724-1433
E-mail: jpaul@usardsguk.army.mil

B. ARL-FERO Personnel

Dr. Hsiang-Yung Yu
Acting Director
Unit 45002, APO AP 96337-5002
Telephone: 011-81-3-3423-1374
Fax: 011-81-3-3423-1832
Email: yuh@arofe.army.mil

Dr. Hiroshi Toyama
Science Advisor-MLC
Unit 45002, APO AP 96337-5002
Telephone: 011-81-3-3423-1374
Fax: 011-81-3-3423-1832
E-mail: toyamah@arofe.army.mil

Dr. Takao Miyata

Science Advisor-MLC
Unit 45002, APO AP 96337-5002
Telephone: 011-81-3-3423-1374
Fax: 011-81-3-3423-1832
E-mail: miyatat@arofe.army.mil

ACRONYMS AND ABBREVIATIONS

A

A/AiTR	Automatic and Aided Target Recognition
AAN	Army After Next
AARL	Army Aviation Research Laboratory
AASERT	Augmentation Awards for Science and Engineering Research Training
ACTD	Advanced Concepts and Technology Demonstration
ADS	Advanced Distributed Simulation
AFDD	ATCOM Aeroflightdynamics Directorate
AFM	Atomic Force Microscopy
AFOSR	Air Force Office of Scientific Research
AIP	American Institute of Physics
AMC	Army Materiel Command
AMCOM	Aviation and Missile Command
AMO	atomic, molecular and optical
AMRDEC	Aviation and Missile Research, Development and Engineering Center
ARC	Advanced Research Center
ARDEC	Armament Research, Development and Engineering Center
ARI	Army Research Institute
AMRICD	Army Medical Research Institute for Chemical Defense
ARL	Army Research Laboratory
ARL/SEDD	Army Research laboratory/Sensors and Electron Devices Directorate
ARL/WMRD	Army Research Laboratory/Weapons and Materials Research Directorate
ARL/WTD	Army Research Laboratory/Weapons Technology
ARNG	Army National Guard
ARO	Army Research Office
ARO-FE	Army Research Office-Far East
ARO-LS	Army Research Office-Life Sciences
ARO-PA	Army Research Office-Pan America
ARO-W	Army Research Office-Washington
ARPA	Advanced Research Projects Agency
ASARDA	Assistant Secretary of the Army for Research, Development, and Acquisition
ASTMP	Army science and Technology Master Plan
ATCOM	Aviation and Troop Command
ATEC	Army Test and Evaluation Command
ATD	Advanced Technology Demonstration
ATIP	Advanced Technology Insertion Program
ATM	asynchronous transfer mode
ATR	automatic target recognition

B

BAST	Board on Army Science and Technology
B-ISDN	Broadband Integrated Services Digital Network
BMDA	Ballistic Missile Defense Agency
BRL-CAD	Ballistic Research Laboratory-Computer Aided Design

C

C^2	command and control
C^3	command, control, and communications
C4ISR	Command, Control, Communications, Computing, Intelligence, Surveillance, and Reconnaissance
CAD	computer-aided design
CAD/CAM	computer-aided design/computer-aided manufacture
CAP	continuous assisted performance
CAPS	Computer-Aided Prototyping System
CARC	chemical agent resistant coatings
CARS	coherent anti-stokes Raman scattering
CB	chemical and biological
CBD	Chemical and Biological Defense
CBDCOM	Chemical and Biological Defense Command
CBI	Compton-backscatter imaging
CD	compact disk
CDMA	code division multiple access
CECOM	Communications Electronic Command
CERL	Corps of Engineers Research Laboratories
CICS	Center on Intelligent Control Systems
CIN/S	Complex Interactive Networks/Systems
CIP	combat information processor
CIS	Computing and Information Sciences
CMP	chemo-mechanical polishing
CNR	Combat Net Radio
CNT	carbon nanotube
COE	Center(s) of Excellence
CPT	cone penetrometer
CRREL	Cold Regions Research and Engineering Laboratory
CTI	Coherent Technologies, Inc.
CVD	chemical vapor deposition
CWA	chemical warfare agent
CW&S	conferences, workshops, and symposia

D

DARPA	Defense Advanced Research Projects Agency
DERA	Defense Evaluation and Research Agency
DAT	Destructive Absorption Technology
DBL	Digital Biomechanics Laboratory
DDR&E	Director, Defense Research and Engineering
DEM	digital elevation model
DEPSCoR	Defense Experimental Program to Stimulate Competitive Research
DERA	Defense Evaluation and Research Agency
DIS	distributed interactive simulation
DLC	diamond-like carbon

DMFC   direct oxidation methanol fuel cells
DoD   U.S. Department of Defense
DoE   U.S. Department of Energy
DOP   depth of penetration
DPI   DoD Polygraph Institute
DPIV   digital particle image velocimetry
DRC   dendron rod coil
DS-CDMA   direct sequence code division multiple access
DTC   Developmental Test Command
DTRA   Defense Threat Reduction Agency
DURINT   Defense University Research Institution in Nanotechnology
DURIP   Defense University Research Instrumentation Program
DX   Data Exchange

E
ECBC   Edgewood Chemical Biological Center
ECCM   electron counter countermeasures
EFP   explosively formed penetrators
EM   electromagnetic
EMI   electromagnetic induction
EMO   electronic, magnetic, and optical
EPRI   Electric Power Research Institute
EQA   equal channel angular
ERC   Engine Research Center
ERDEC   Edgewood Research, Development and Engineering Center
ERO   European Research Office

F
FCS   Future Combat System
FDA   Food and Drug Administration
FDF   finite dimensional filter
FDTD   finite different time domain
FEA   field emitter arrays
FF   future force
FFRDC   Federally Funded Research and development Center
FGM   functionally graded material
FISST   finite set statistics
FLIR   forward-looking infrared
FOC   force operating capabilities
FREP   Faculty Research and Engineering Program
FRI   focused research initiative
FY   fiscal year

G

GFA	glass forming ability
GHz	gigahertz
GICUR	Governmental Industry Cooperative University Research
GIS	Geographic Information System
GPa	giga pascal
GPI	General Physics Institute
GPR	ground penetrating radar
GPS	global positioning system
GSL	Geotechnical and Structures Laboratory

H

HBCU/MI	Historically Black Colleges and Universities/Minority Institutions
HCES	high confidence embedded systems
HEL	high energy laser
HEMT	high-electron-mobility transistor
H&HS	Health and Human Services
HICIST	Human Intelligence Counterintelligence Support Tool
HQDA	Headquarters, Department of the Army
HQUSACE	Headquarters, U.S. Army Corps of Engineers
HRED	Human Research and Engineering Directorate
HIS	Hispanic Serving Intitutions
HSSMF	(Summer Associateship Program for) High School Science and Mathematics Faculty
HSTAMIDS	Handheld Standoff Mine Detection System
Hz	hertz

I

IA	Intelligent Agent
IC	integrated circuit
ICASE	Institute for Computer Applications in Science and Engineering
ICB	Institute for Collaborative Biotechnologies
ICT	Institute for Creative Technology
IEEE	Institute of Electrical and Electronics Engineers, Inc.
IFC	international fuel cells
IIL	imaging interferometric lithography
IMS	intelligent munitions systems
INEL	Idaho National Engineering Laboratory
IPC	interpenetrating phase composite coatings
IR	infrared
ISEP	International Science and Engineering Fair
ISI	Infrastructure Support Instrumentation
ISN	Institute for Soldier Nanotechnologies
ISP	Infrastructure Support Program

J

JCIS	Joint Conference on Information Science
JPEG	Joint Photographic Experts Group
JSEP	Joint Services Electronics Program
JSHS	Junior Science and Humanities Symposium
JUXOCO	Joint Unexploded Ordnance Coordinating Office

K

K	Kelvin
km	kilometer

L

LANL	Los Alamos National Laboratory
LC	liquid crystal
LCD	liquid crystal display
LDV	laser-Doppler velocimetry
LED	light emitting diode
LES	large eddy simulation
LIA	logistics integration activity
LIDAR	laser radar
LLNL	Lawrence Livermore National Laboratory
LMR	lateral migration radiography
LPI	low probability of interception
LRCP	Laboratory Research Cooperative Program

M

MAD	mesoscale actuator device
MARRS	multifunctional adaptive radio, radar and sensors
MBE	molecular beam epitaxy
MB	microbiology and biodegradation
MCAGCC	Marine Corps Air Ground Combat Center
MCNC	Microelectronics Center of North Carolina
MDA	Missile Defense Agency
MEA	membrane electrode assembly
MEMS	microelectromechanical systems
MEP	mobile electric power
MESFET	metal epitaxial semiconductor field effect transistor
MGG	molecular, genetics and genomics
MHz	megahertz
MICOM	(Army) Missile Command
MIMD	multiple instruction, multiple data
MIME	mixed-mode electronics
MIND	meandering instantaneous diffusion
MIP	molecular imprinted polymer
MIRSL	Microwave Remote Sensing Laboratory
MITS	(IEEE) Microwave Theory and Techniques Society

ML	majority logic
MM	manually mixing technology
MMC	metal matrix composites
MMI	Michigan Molecular Institute
MMLRR	multimedia least resistance routing
MMW	millimeter wave
MOCVD	metal-organic chemical vapor deposition
MOMBE	molecular beam epitaxy
MOOSE	Multispectral Omnidirectional Optical SEnsor
MOT	magneto-optic trap
MPa	mega pascal
MPA	multipass amplifier
MQW	multiple quantum well
MRMC	Medical Research and Materiel Command
MS	Materials Science (Division)
MTF	modulation transfer function
MTT-S	Microwave Theory and Techniques Society
MUD	Multiuser Detection
MURI	Multidisciplinary University Research Initiative (Program)
mW	milliwatt

N

NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NBC	nuclear, biological, and chemical
NBIF	National Biotechnology Information Facility
NBL	nocturnal boundary layer
NDSEG	National Defense Science and Engineering Graduate (Fellowship Program)
NIST	National Institute of Standards and Technology
nm	nanometer
NPS	Naval Postgraduate School
NRDEC	Natick Research, Development and Engineering Center
NSC	Natick Soldier Center
NSF	National Science Foundation
NVEOSD	Night Vision and Electro-Optics Systems Directorate
NVESD	Night Vision and Electronics Sensors Directorates
NVL	Night Vision Lab

O

O&S	operation and support
OACSIM	Office of Assistant Chief of Staff Installation Management
OCB	Operation Cherry Blossom
OCONUS	outside continent of United States
ODDRE	Office of the Director for Defense Research and Engineering

OEIC	optoelectronic integrated circuits
OF	Objective Force
OMA	Operations and Maintenance Army
ONR	Office of Naval Research
ORNL	Oak Ridge National Laboratory
OSCR	operations and support cost reduction
OSD	Office of the Secretary of Defense
OUSD	Office of the Under Secretary of Defense

P

PASIS	Perpetually assured information security
PC	pathogens countermeasures
PC	personal computer
PCR	polymerase chain reaction
PDI	point diffraction interferometry
PE	process element
PECASE	Presidential Early Awards for Scientists and Engineers
PEM	proton exchange membrane
PEO	program executive officer
pHEMT	p-type high electron mobility transistor
PIV	particle imaging velocimetry
PLIF	planar laser-induced fluorescence
PLRCP	Post Laboratory Research Cooperative Program
PM	program manager
PSD	Physical Sciences Directorate
PSD	preventing sleep deprivation
PSFREP	Post Summer Faculty Research and Engineering Program
PZT	piezo electric ceramics

Q

QCL	quantum cascade laser
QCT	quasi-classical trajectory
QDIP	quantum dot infrared photodetector
QDSL	quantum dot superlattice structures
QoS	quality of service
QR	quadruple resonance
QW	quantum well
QWIP	quantum well infrared photodetector
QWP	quarter-wave plate

R

R&D	research and development
RAM	random access memory
RANS	Reynolds-averaged Navier-stokes solver
RDEC	Research, Development and Engineering Center

REDCOM   US Army Research, Development, and Engineering Command
RDT&E   Research, Development, Test and Evaluation
REAP   Research and Engineering Apprenticeship Program
RE   rare earth
RF   radio frequency
RFI   radio frequency interference
RIACS   Research Institute for Advanced Computer Science
RLS   recursive least squares
RPA   random phase approximation
RPI   Rensselaer Polytechnic Institute
RSA   reverse saturable absorber
RSTA   reconnaissance, surveillance, and target acquisition
RTI   Research Triangle Institute
RTM   resin transfer molding

S

SACC   Strategic and Advanced Computing Center
SAM   self-assembled monolayers
SANS   small neutron scattering
SAW   surface acoustic waves
SAXS   small-angle x-ray scattering
SBCCOM   Soldier Biological and Chemical Command
SBIR   Small Business Innovation Research (Program)
SCAPS   site characterization and penetrometer system
SCF   surface crack inflexure
SCWO   supercritical water oxidation
SEDD   Sensors and Electronics Devices Directorate
SERDP   Strategic Environmental Research, Development Program
SET   single-electron transistors
SEVNB   single edge V-notch beam
SFM   surface force microscopy
SFREP   Summer Faculty Research and Engineering Program
SGS   subgrid scale
SHIFT   simulation of hybrid multi-modal systems
SHS   self-propagating high temperature synthesis
SIFT   scale invariant feature transform
SINCGARS   Single Channel Ground and Airborne Radio System
SKBS   Software and Knowledge–based Systems
SLAP   Sabot launched armor penetrator
SMDC   Space and Missile Defense Command
SME   science, mathematics, and/or engineering
SMMW   submillimeter wave
SNL   Sandia National Laboratories
SOCOM   Special Operations Command
SPH   smooth particle hydrodynamics

SPICE	simulation program for integrated circuit emulation
SRO	strategic research objective
SSCOM	Soldier Systems Command
SSP	Scientific Services Program
STAR	scaled tangent rotation
STAS	short term analysis services
STIR	Short Term Innovative Research (Program)
STM	scanning tunnelling microscopy
STO	Science and Technology Objectives
STRICOM	Simulation, Training and Instrumentation Command
STTR	Small Business Technology Transfer (Program)

T

T	tesla
TACOM	Tank-Automotive and Armament Command
TARDEC	Tank and Automotive Research, Development and Engineering Center
TCP/IP	transport control protocol/Internet protocol
TCU	Tribal Colleges and Universities
TE	thermoelectric
TEC	Topographic Engineering Center
TECOM	Test and Evaluation Command
TEP	turbulence eddy profiler
THz	terahertz
TOPS	Turnable Optical Polymer Systems
TIN	triangualted irregular networks
TRAC	Training and Doctrine Command Analysis Center
TRADOC	Training and Doctrine Command
TTCP	The Technical Cooperation Programs

U

UARC	University Affiliated Research Center
UCF	universal conductance fluctuations
UHF	ultra high frequency
URI	University Research Initiative
UNITE	Uninitiates Introduction to Engineering
URISP	University Research Initiative Support Program
USACE	U.S. Army Corps of Engineers
USAF	U.S. Air Force
USCG	U.S. Coast Guard
USDI	U.S. Department of Interior
USMC	U.S. Marine Corps
USN	U.S. Navy
USRDSG-UK	U.S. Research, Development, and Standardization Group-United Kingdom
UV	ultra violet
UWB	ultra wide bandwidth

UXO	unexploded ordinance

V

VCO	voltage controlled oscillator
VCSEL	vertical cavity surface emitting laser
VESPER	Visualization Environment for Supporting Photogammetry Exploitation Research
VHSIC	very high-speed integrated circuit
VISTA	very intelligent surveillance and target acquisition
VLC	variable length coding
VLSI/ULSI	very-large-scale and ultra-large-scale integration
VPERI	virtual part and engineering research initiative

W

WAAMD	wide area airborne minefield detection
WAXD	wide-angle x-ray diffraction
WDM	wavelength division multiplexing
WES	Waterways Experiment Station
WMRD	Weapons and Materials Research Directorate
WMD	weapons of mass destruction
WRAIR	Walter Reed Army Institute of Research
WSR-88D	Weather Surveillance Radar 1988-Doppler

Y

YIP	Young Investigator Program